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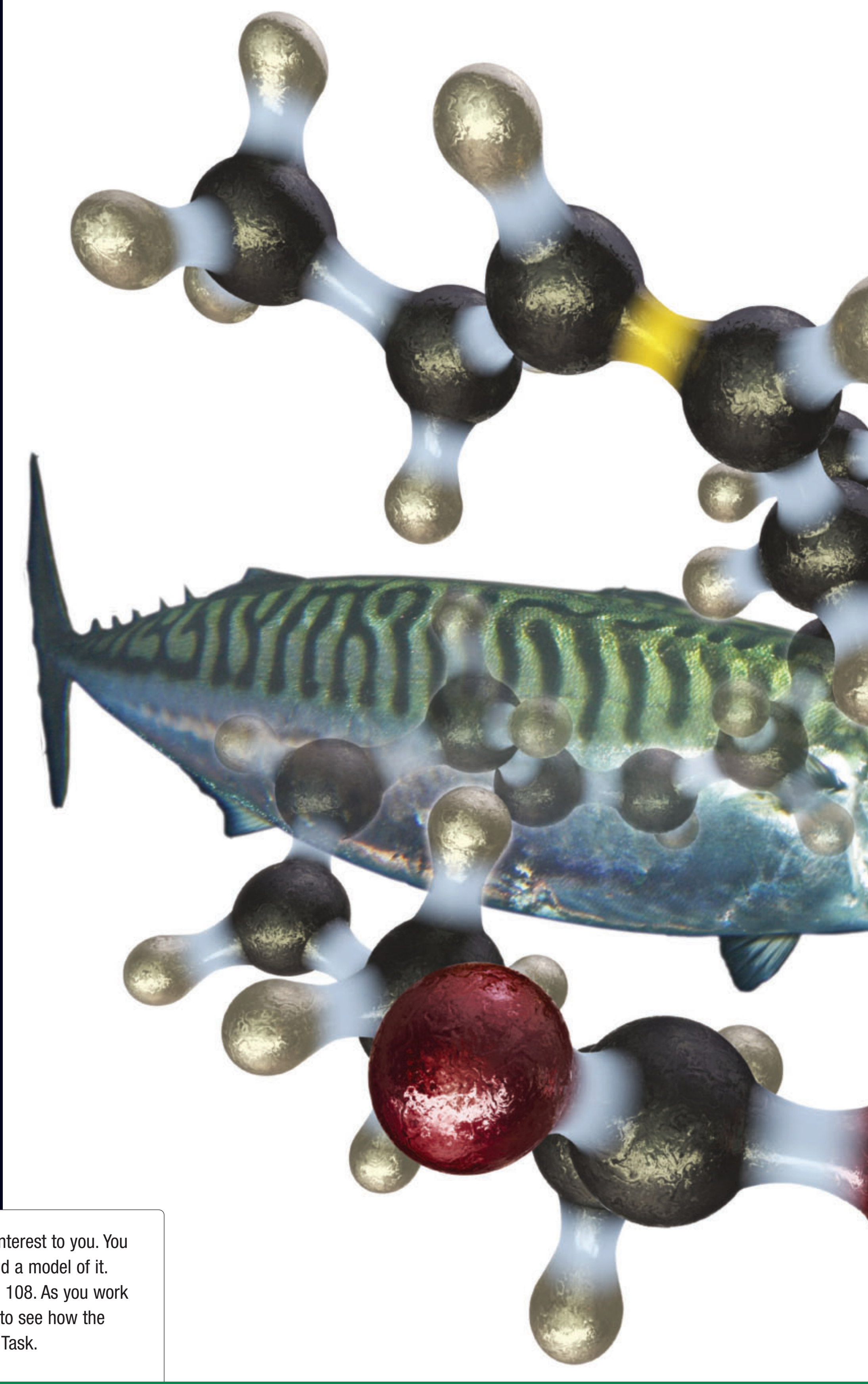
UNIT 1 Biochemistry



OVERALL EXPECTATIONS

- analyze technological applications of enzymes in some industrial processes, and evaluate technological advances in the field of cellular biology
- investigate the chemical structures, functions, and chemical properties of biological molecules involved in some common cellular processes and biochemical reactions
- demonstrate an understanding of the structures and functions of biological molecules, and the biochemical reactions required to maintain normal cellular function

BIG IDEAS

- Technological applications that affect biological processes and cellular functions are used in the food, pharmaceutical, and medical industries.
- Biological molecules and their chemical properties affect cellular processes and biochemical reactions.
- Biochemical compounds play important structural and functional roles in the cells of all living organisms.

UNIT TASK **PREVIEW**

In this Unit Task, you will select a molecule of interest to you. You will research its structure and function and build a model of it.

The Unit Task is described in detail on page 108. As you work through the unit, look for Unit Task Bookmarks to see how the information you are learning relates to the Unit Task.

PROMOTING THE GOOD FATS

Did you know that eating a tin of sardines may actually help you improve your marks in school? Sardines contain macromolecules, or large molecules, called omega-3 fatty acids. Omega-3 fatty acids are essential fatty acids. They are needed to maintain human health. Our cells, however, do not produce omega-3 fatty acids on their own, so we must obtain them through the foods we eat. Fatty fish, such as mackerel, salmon, and sardines, are rich sources of omega-3, as are nuts, oils, and other plant sources. In recent years, the popularity of omega-3 fatty acids has increased. Research has shown that omega-3 fatty acids play a significant role in brain function, cardiovascular health, and the production of healthy skin. In fact, the Heart and Stroke Foundation of Canada recommends eating fish such as sardines, mackerel, lake trout, herring, albacore tuna, and salmon at least twice a week to maintain optimal levels of omega-3 fatty acids. Foods such as eggs and orange juice may also contain omega-3 fatty acids.

Other scientific research shows that eating a diet rich in omega-3 fatty acids reduces the risk of inflammation and may help to reduce the risk of chronic diseases, such as heart disease, cancer, and arthritis. The neurons in the human brain use omega-3 fatty acids for important cognitive and behavioural functions. Babies have a greater risk of developing vision and nerve problems if their mother lacks omega-3 fatty acids in her diet during pregnancy. Omega-3 fatty acids may also be useful for treating a number of conditions in adults, such as high cholesterol, high blood pressure, diabetes, depression, skin disorders, and asthma. People who do not consume enough omega-3 in their diet may suffer from fatigue, poor memory, dry skin, heart problems, mood swings or depression, and poor circulation.

It is important to obtain a balance of all nutrients, including omega-3 fatty acids, in your diet. All organisms use and rely on thousands of different types of molecules for the proper functioning of their cells. Some of these molecules can be obtained directly in the organism's diet. Other molecules are synthesized from building blocks contained in their diet. In either case, the consumption of an appropriate mix of nutrient molecules is essential to meet the demands of cells.

Questions

1. Were you already aware of the importance of omega-3 fatty acids in your diet? Are there other essential nutrients that you have heard about? In which foods can these nutrients be found?

2. The foods we eat provide us with a balance of carbohydrates, fats, and proteins. All of these nutrients are essential for a healthy body. How do you think carbohydrates, fats, and proteins compare, in terms of their chemical and physical properties?

3. Living organisms can make many "custom" molecules. For example, spiders produce silk molecules from custom proteins, while humans use another set of proteins to grow hair. What properties might these two types of proteins share? In what ways might they be different?

4. Do you think it is better to obtain omega-3 fatty acids from foods that contain them or from a supplement? Explain your reasoning.

UNIT 1 ARE YOU READY?

CONCEPTS

- understand acid, base, and neutralization reactions
- explain the laws of conservation of mass and energy
- explain the role(s) of carbohydrates, proteins, and fats in the body for cell membrane function
- differentiate between diffusion and osmosis
- understand the role of carbon in biochemical molecules
- understand the role of nucleic acids

SKILLS

- determine the number of atoms in different molecules, based on chemical formulas
- determine the atomic mass of different compounds
- balance chemical equations
- differentiate between combustion and neutralization reactions
- draw structural diagrams of the reactants and products in a reaction
- draw Lewis diagrams

Concepts Review

1. Describe the difference between an atom and an ion. K/U
2. What type of bond within a molecule holds the atoms of the molecule together? K/U
3. Compare the following: an element, a compound, and a mixture. K/U
4. Describe the difference between an ionic bond and a covalent bond. K/U
5. (a) How many covalent bonds does each of the following type of atom typically form?
    (i) H
    (ii) O
    (iii) C
    (iv) N
   (b) How is the number of covalent bonds formed by an atom related to its number of valence electrons? K/U T/I
6. Match each term on the left with the most appropriate description on the right. K/U
   (a) pure substance
   (b) mixture
   (c) solution
   (d) suspension
   (i) two or more substances
   (ii) a substance made from only one kind of particle
   (iii) substances in two different phases that do not settle out
   (iv) one substance dissolved in another substance
7. (a) Does an acid or a base increase the concentration of H^+ ions in a solution?
   (b) Does an acid or a base increase the concentration of OH^- ions in a solution?
   (c) What is the result of a neutralization reaction between an acid and a base?
   (d) List several distinctive properties of acids and of bases.
   (e) How is acidity related to the pH value of a solution? K/U
8. Electrons in a molecule will repel each other and move as far away from each other as possible. How does this explain why a water molecule has a bent shape instead of being linear (**Figure 1**)? T/I

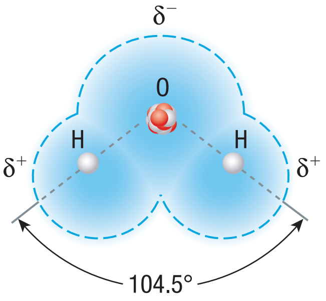


Figure 1

9. (a) What is the law of conservation of mass?
   (b) How is the law of conservation of mass demonstrated in biological systems such as food chains? K/U
10. (a) What is the law of conservation of energy?
    (b) How is the law of conservation of energy demonstrated in biological systems such as food chains? K/U
11. (a) Name the labelled cellular structures in **Figure 2**, and describe their functions.
    (b) Does Figure 2 show an animal cell or a plant cell? Explain your reasoning. K/U

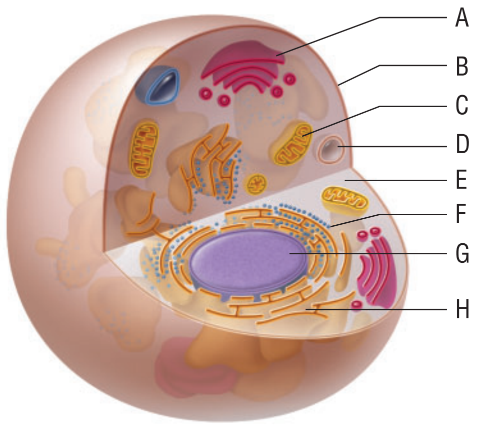


Figure 2

12. Examine the two equations below. How are they related? T/I

photosynthesis: $6\ H_2O + 6\ CO_2 \rightarrow C_6H_{12}O_6 + 6\ O_2$

cellular respiration: $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$

13. Match each macromolecule on the left with the most appropriate description on the right. K/U

(a) fats	(i) directly involved with inheritance
(b) proteins	(ii) range from small sugar molecules to large starch molecules
(c) carbohydrates	(iii) responsible for long-term energy storage; also called lipids
(d) nucleic acids	(iv) one or more folded and coiled polypeptides; made of amino acids

14. (a) Define osmosis and diffusion.
    (b) Make a sketch to represent each process in (a). Label your sketch.
    (c) Explain why these processes are essential for cellular function. K/U C

15. Draw a diagram to explain what happens to a cell in each of the following types of solutions. K/U C
    (a) isotonic
    (b) hypotonic
    (c) hypertonic

Skills Review

16. Copy **Table 1** into your notebook and complete it. (For atomic mass, round to the nearest whole number.) T/I

Table 1

Name of element	Symbol	Number of protons	Number of neutrons	Atomic mass
neon				20
	Cl	17		
		28	31	
				52
			110	

17. Determine the number of atoms and the atomic mass of each atom in each of the following molecules. Then calculate the total atomic mass for each molecule. T/I
    (a) methane, CH_4
    (b) glucose, $C_6H_{12}O_6$
    (c) cysteine, $C_3H_7NO_2S$

18. Write the balanced chemical equation for each of the following reactions. T/I
    (a) $CH_4 + O_2 \rightarrow CO_2 + H_2O$
    (b) $CH_2O_2 \rightarrow C_2H_2O_3 + H_2O$
    (c) $C_6H_{12}O_6 \rightarrow C_2H_6O + CO_2$

19. Examine the equations below. T/I
    (i) $HCl + NaOH \rightarrow NaCl + H_2O$
    (ii) $2\ C_2H_6 + 7\ O_2 \rightarrow 4\ CO_2 + 6\ H_2O$
    (a) Which equation represents a combustion reaction? Explain your reasoning.
    (b) Which equation represents a neutralization reaction? Explain your reasoning.

20. Draw structural diagrams to represent the reactants and products in the combustion reaction between methane, CH_4, and oxygen, O_2. T/I C

21. How are cellular respiration and the combustion of methane similar? K/U T/I

22. Draw the Lewis diagram for each molecule. C
    (a) water, H_2O
    (b) carbon dioxide, CO_2
    (c) ethane, C_2H_6

CAREER PATHWAYS **PREVIEW**

Throughout this unit, you will see Career Links. Go to the Nelson Science website to find information about careers related to biochemistry. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that describes the educational requirements for these careers, as well as some career-related questions for you to research.

CHAPTER 1 The Biochemical Basis of Life

KEY CONCEPTS

After completing this chapter you will be able to

- describe the types of bonds that are found in biological molecules and interactions
- describe the unusual properties of water
- compare the functional groups that contribute to the structure and function of biological molecules
- describe how the reactions involved in biochemical processes can be subdivided into major classes and contribute to normal cellular function
- describe the major classes of biological molecules and their structural and functional roles
- understand that enzymes are involved in all biochemical reactions controlled by the cell
- compare technologies that use and manipulate enzymes to achieve a desired product or process
- understand the potential environmental and social impacts of various biochemical technologies

What Types of Chemicals Make Up Living Things?

Every second, millions of complex chemical reactions are taking place in your body. Your cells are continuously working and carrying out these reactions, without any disruption in your daily activities. Your cells are mixtures of thousands of different chemical compounds, which are arranged into various cellular structures and perform a myriad of tasks. For example, more than a dozen chemical enzymes, such as DNA polymerase, DNA ligase, primase, helicase, and topoisomerase, are required to drive DNA replication in your cells. The process of active cellular transport requires proteins, such as channel proteins, aquaporins, and carrier proteins. Many of your cells transport chemicals that are used in other parts of your body. For example, your red blood cells contain the chemical hemoglobin, which is essential for transporting oxygen throughout your body.

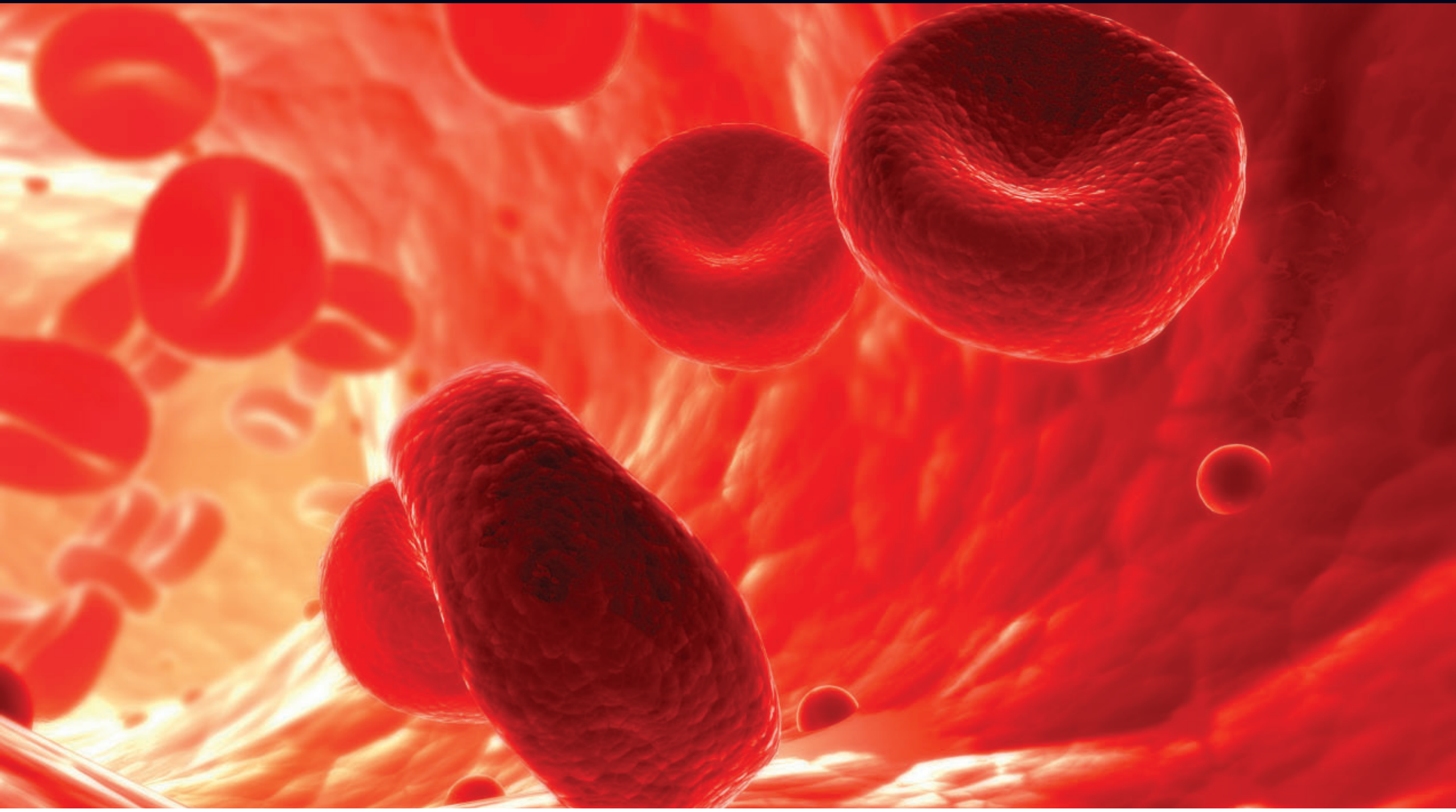
Cells come in many types and have numerous functions. At their most basic, they are tiny packages of self-replicating chemical processors. They are organized to work together and against each other to sustain life. Therefore, knowledge of the fundamental concepts of chemistry is necessary to understand how living systems function. Scientists have a deep understanding of the chemical basis of life, but there are still many unsolved mysteries.

At the core of all cellular structures and processes are four main groups of organic compounds. These compounds include a wide variety of carbohydrates, fats (lipids), proteins, and nucleic acids. These compounds must be either synthesized by the cell or consumed in foods, in forms that can either be used immediately by the cells or that can be dismantled and rearranged. As you will learn in this chapter, these four types of compounds are responsible for thousands of functions and interactions performed by the cells. Biological macromolecules can react with oxygen in the cells to provide chemical energy in biological systems. Some molecules, such as omega-3 fatty acids, which are contained only in certain foods, can help to fight off diseases and illnesses. Collectively, the four biological macromolecules enable cells to function. Understanding how these molecules carry out their roles will help you understand how your body functions from day to day.

STARTING **POINTS**

Answer the following questions based on your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills you have learned in the chapter.

1. (a) What kind of foods do you think of when you hear the terms “carbohydrates,” “fats,” and “proteins”?
   (b) How do you think carbohydrates, fats, and proteins compare in terms of their chemical and physical properties?
   (c) Suggest ways that your body uses these nutrients, and explain how an excess of these nutrients could have a negative impact on your body.
2. The molecules of living things exhibit a very wide range of chemical and physical properties. Brainstorm some of the properties that might be particularly useful for molecules that serve the following biological roles:
   (a) an energy storage molecule
   (b) protection from predators
   (c) a catalyst
   (d) the building material for a cell membrane



Mini Investigation

Getting Physical with Biochemistry

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1

When living things use a biological substance to perform a task, the substance must have suitable properties. One of the most important properties of a biological substance is solubility. In this activity, you will examine the solubility and physical state of some common biological substances.

Equipment and Materials: balance; test tubes; stirring rods; 500 mL beaker; distilled water; hot water; samples such as starch, glucose, sucrose, cellulose fibre, egg albumin, beeswax, butter, olive oil, and table salt

1. Measure 0.1 g of each substance.
2. Add each weighed sample to 10 mL of distilled water in a labelled test tube. Stir each mixture.
3. Fill the beaker with hot water from the tap. You will use this as a water bath.
4. Place the test tubes in the water bath, and stir each mixture vigorously for 1 min.
5. Record the state of each substance (solid or liquid) and its solubility.

A. How do you think the solubility of a substance affects its chemical reactivity in solution? T/I

B. Suggest reasons why some substances dissolve in water, while others do not. How do you think the size of a molecule affects its solubility? T/I

C. How might the properties of wax be useful for living things? T/I

D. Which of the substances you tested formed a suspension, rather than a solution, in water? How do you know? T/I

E. Do you think blood is an example of a solution, a suspension, or both? Explain. K/U

F. Consider milk and other suspensions in nature that contain suspended proteins and fats. How do they differ from solutions and why might suspensions be particularly valuable for living things? T/I

1.1

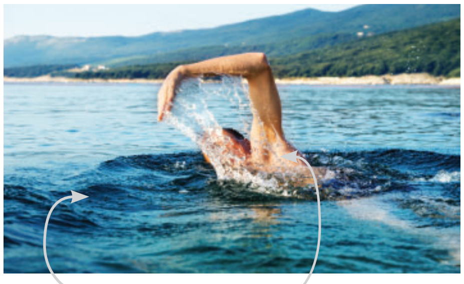
The Fundamental Chemistry of Life

As you learn about all living organisms, you will study everything from the microscopic subatomic level all the way to the macroscopic level of the organism. You will begin to understand how everything is uniquely adapted to provide a specific structure and function. You will soon see that the properties of life stem from a hierarchical arrangement of chemical parts.

Matter makes up everything in the universe, including all living organisms. Matter is composed of elements. An element is a pure substance that cannot be broken down into simpler substances using ordinary chemical or physical techniques. The smallest particle of an element is an atom. Elements differ from one another in their atomic structure. Atoms often bind to each other chemically in fixed numbers and ratios to form molecules. For example, the oxygen gas we breathe is formed from the chemical combination of two oxygen atoms. A chemical compound is a stable combination of different elements that are held together by chemical bonds. In the study of biology, you will encounter a great variety of chemical compounds.

The chemistry of life inside a cell is complex in terms of the sizes and shapes of molecules and their functions in chemical reactions. Even so, all organic (carbon-containing) compounds in living organisms are composed primarily of carbon, C; hydrogen, H; and oxygen, O. As well, they often include nitrogen, N. There are about 21 other elements found in living organisms, but these four elements make up 96 % of the weight of a living organism (**Table 1**). Most of the other 4 % is composed of only seven other elements: calcium, Ca; phosphorus, P; potassium, K; sulfur, S; sodium, Na; chlorine, Cl; and magnesium, Mg. These elements often occur as ions or in inorganic compounds within living organisms. The rest of the elements that are required by organisms are found in such small amounts (< 0.1 %) that they are called trace elements. Iodine, I, and iron, Fe, are examples of trace elements. A deficiency in any trace element can lead to health problems.

Table 1 Percentage Composition of Selected Elements in Living and Non-living Things

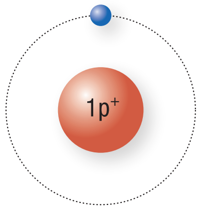


Seawater	%	Human	%
oxygen	88.3	oxygen	85.0
hydrogen	11.0	hydrogen	10.7
chlorine	1.9	carbon	3.3
sodium	1.1	potassium	0.34
magnesium	0.1	nitrogen	0.16
sulfur	0.09	phosphorus	0.05
potassium	0.04	calcium	0.02
calcium	0.04	magnesium	0.01
carbon	0.003	iron	0.008
silicon	0.0029	sodium	0.001
nitrogen	0.0015	zinc	0.0002
strontium	0.0008	copper	0.0001

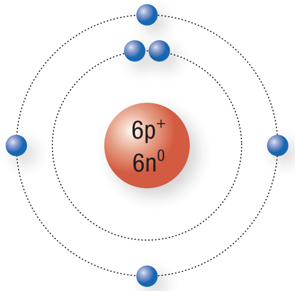
Pumpkin	%	Earth's crust	%
oxygen	65.0	oxygen	46.6
carbon	18.5	silicon	27.7
hydrogen	9.5	aluminum	8.1
nitrogen	3.3	iron	5.0
calcium	2.0	calcium	3.6
phosphorus	1.1	sodium	2.8
potassium	0.35	potassium	2.6
sulfur	0.25	magnesium	2.1
sodium	0.15	other elements	1.5
chlorine	0.15		
magnesium	0.05		
iron	0.004		
iodine	0.0004		

Atomic Structure

Elements consist of individual atoms: the smallest units that retain the chemical and physical properties of a particular element. An atom is composed of three subatomic particles: protons, neutrons, and electrons. The number of protons in an atom defines its elemental identity (**Figure 1**). Protons and neutrons are located in the nucleus. Electrons are located in the region surrounding the nucleus. Protons have a positive charge, neutrons have no charge, and electrons have a negative charge. An atom has no net charge because the number of protons is equal to the number of electrons.



(a) hydrogen



(b) carbon

Figure 1 The basic atomic structure of (a) hydrogen and (b) carbon

The atomic number of an element is equal to the number of protons in the element. For example, carbon has an atomic number of 6, so all carbon atoms have 6 protons in their nucleus. A carbon atom also has 6 electrons. The number of neutrons in the nucleus can vary, as you will learn later in this section.

The mass number of an atom is the total number of protons and neutrons in the nucleus. Electrons are not included in this number because the mass of an electron is negligible compared with the mass of a proton or neutron. The mass of an atom is therefore determined by the number of protons and neutrons it contains. **Table 2** lists the atomic numbers and mass numbers of the most common elements in living organisms. The atomic symbol of an element is sometimes shown with the element's atomic number and mass number (**Figure 2**).

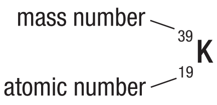


Figure 2 Potassium, K, has 19 protons and 20 neutrons in its nucleus.

Table 2 Atomic Number and Mass Number of the Most Common Elements in Living Organisms

Element	Symbol	Atomic number	Mass number of the most common form
hydrogen	H	1	1
carbon	C	6	12
nitrogen	N	7	14
oxygen	O	8	16
sodium	Na	11	23
magnesium	Mg	12	24
phosphorus	P	15	31
sulfur	S	16	32
chlorine	Cl	17	35
potassium	K	19	39
calcium	Ca	20	40
iron	Fe	26	56
iodine	I	53	127

Isotopes and Radioisotopes

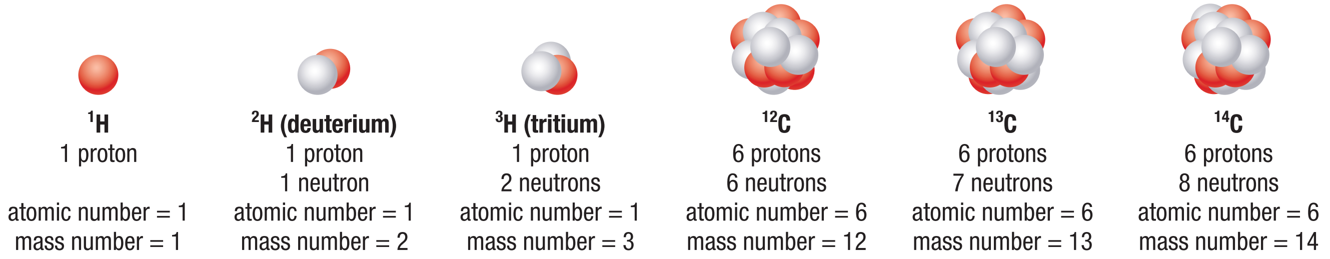
All atoms of the same element have the same number of protons, but they may have different numbers of neutrons in the nucleus. This means that atoms with the same atomic number can have different atomic masses. **Isotopes** are different forms of the same element, with different atomic masses. Because isotopes of the same element have the same number of protons and electrons, they behave exactly the same in a chemical reaction.

isotope a form of an element that differs in its number of neutrons

RADIOISOTOPES AND RADIOACTIVE TRACERS

radioisotope a radioactive isotope of an element

The nuclei of some isotopes of an element are unstable and tend to break down, or decay, giving off particles of matter that can be detected as radioactivity. The decay process transforms an unstable, radioactive isotope—called a **radioisotope**—into an atom of another element. For example, both hydrogen and carbon have three isotopes, which all behave the same in a chemical reaction (**Figure 3**). A carbon isotope with the atomic mass 12 (called carbon-12 or ^{12}C) has 6 neutrons, 6 electrons, and 6 protons. Carbon-12 accounts for 99 % of all the carbon in nature. The isotope ^{13}C has 7 neutrons, 6 electrons, and 6 protons. Like ^{12}C, ^{13}C is a stable isotope. A third isotope, ^{14}C, has 8 neutrons, 6 electrons, and 6 protons. ^{14}C is an unstable radioisotope of carbon. It decays, giving off particles and energy. As it decays, one neutron splits into a high-energy electron and a proton. The isotope then has 7 neutrons, 7 electrons, and 7 protons. This is characteristic of the most common form of the element nitrogen. Thus, the decay of ^{14}C transforms the carbon atom into ^{14}N, a nitrogen atom.



(a) nuclei of the different isotopes of hydrogen

(b) nuclei of the different isotopes of carbon

Figure 3 Comparison of the nuclei of different isotopes of (a) hydrogen and (b) carbon

Radioactive decay continues at a steady rate, with a constant proportion of radioisotope atoms breaking down during a given time interval. The rate of decay of a radioisotope is independent of chemical reactions or environmental conditions, such as temperature or pressure. The radiation from decaying isotopes may damage molecules in living cells, thus harming the organism. However, some radioisotopes are useful in geological and biological research because of their steady rate of decay. They provide scientists with information about the age of organic materials, rocks, and fossils. As well, radioisotopes have numerous medical applications and uses in instrumentation to elucidate the structures of unknown compounds.

Radioisotopes generally behave the same way in cells as non-radioactive isotopes of the same element. However, because radioisotopes give off a radioactive signal as they decay, they are easily detectable in a cell. Radioactive tracers are radioisotopes that are used to follow a specific chemical through a chemical reaction. Using the particles emitted by a radioisotope as a signal, scientists and doctors can trace the path of the radioisotope as it moves through the cells to different locations in the body. In this way, radioisotopes have found many applications in biological, chemical, and medical research. Scientist Melvin Calvin, a pioneer in the study of photosynthesis, used ^{14}C-labelled molecules to determine the sequence of reactions in photosynthesis. Radioisotopes are used to study many biochemical reactions and to perform basic techniques, such as DNA sequencing. Since most biological compounds contain carbon and hydrogen, ^{14}C and ^{3}H (tritium) are commonly used as tracers in biological research.

Radioisotopes are also used in the relatively new field of nuclear medicine to help with the diagnosis and treatment of diseases. For example, the thyroid gland produces hormones that affect growth and metabolism. This gland, located in front of the trachea, is the only organ of the body that actively absorbs iodine. If a patient's symptoms indicate an abnormal level of thyroid hormone output, the physician may inject a small amount of radioactive iodine-131 into the patient and then use a photographic device to scan the thyroid gland. The radioactivity produces an image that is similar to an X-ray, which helps to identify the possible causes of the condition.

CAREER LINK WEB LINK

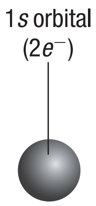
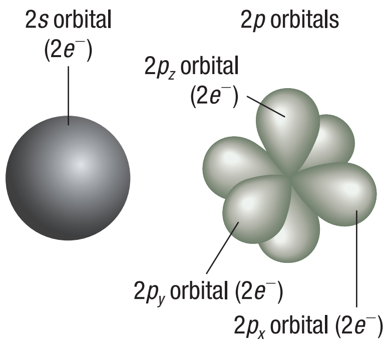
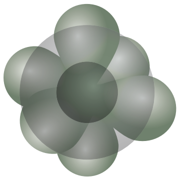
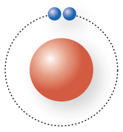
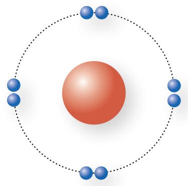
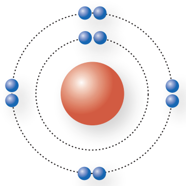
Electron Arrangements

The arrangement of electrons determines the chemical properties of an atom, because only electrons are usually directly involved in a chemical reaction. Recall that the number of electrons in an atom is equal to the number of protons in the nucleus. Since the electrons carry a negative charge that is exactly equal in magnitude but opposite to the positive charge of the protons in the nucleus, the atom is electrically neutral. Electrons move around the atomic nucleus in specific regions, called orbitals. An **orbital** is a region of space that one or two electrons can occupy. Even though one or two electrons may occupy a given orbital, the most stable and balanced condition occurs when the orbital contains two electrons. Electron orbitals are grouped into energy levels, which are sometimes called energy shells. These energy shells are numbered 1, 2, 3, and so on, indicating their relative distance from the nucleus. The lowest energy shell of an atom is closest to the nucleus. A maximum of two electrons can occupy the lowest energy shell. The second and third energy shells hold up to eight and 18 electrons, respectively.

orbital a region of space that is occupied by electrons located around the nucleus of an atom

The first electron shell, the 1*s* orbital, is a single spherical orbital (**Table 3**). Hydrogen, for example, has only a 1*s* electron orbital, containing one electron. Similarly, helium has only a 1*s* electron orbital, but it contains two electrons. Atoms with more than two electrons have higher energy levels. The shell at the second energy level consists of a 2*s* orbital and three 2*p* orbitals. The 2*s* orbital is spherical in shape. Each 2*p* orbital shape looks like two balloons tied together. The three 2*p* orbitals bisect in the centre at right angles to each other, giving the orbitals their overall shape. The orbital that is occupied by an electron is what determines the energy level of the electron. The farther away the electron is from the nucleus, the greater its energy. The balloon-like 2*p* orbitals contain electrons that are farther away from the nucleus than the electrons in the 2*s* orbital, and thus hold the electrons with a higher energy level. In large atoms, some higher-energy electrons occupy *d* and *f* orbitals, which have even more complex shapes.

Table 3 Types of Electron Orbitals

	1*s* orbital	2*s* and 2*p* orbital	Neon: 1*s*, 2*s*, 2*p*
Electron orbitals		 2*s* orbital ($2e^-$) 2*p* orbitals $2p_z$ orbital ($2e^-$) $2p_y$ orbital ($2e^-$) $2p_x$ orbital ($2e^-$)	
Electron-shell diagrams			

Valence electrons are the electrons in an atom's outermost energy shell, or valence shell. Atoms with an outermost energy shell that is not completely filled with electrons tend to be chemically reactive atoms. Atoms with a completely filled outermost energy level are chemically inactive, or inert. For example, hydrogen has a single electron in the 1*s* shell, its outermost shell. Hydrogen is a highly reactive element. The helium atom is chemically inert because it has two electrons in its 1*s* shell,

valence electron an electron in the outermost energy level or shell of an atom

Table 4 Valence Electron Shell of Common Biological Elements and Helium

Atomic number	Element	Lewis dot diagram	Valence shell
1	hydrogen	$H\cdot$	$1s^1$
6	carbon	$\cdot\dot{\underset{\cdot}{C}}\cdot$	$2s^2\,2p^2$
7	nitrogen	$\cdot\ddot{\underset{\cdot}{N}}\cdot$	$2s^2\,2p^3$
8	oxygen	$\cdot\ddot{\underset{\cdot}{O}}:$	$2s^2\,2p^4$
2	helium	$He:$	$1s^2$

its outermost shell. (**Table 4**). Neon has all eight positions in its outer shell occupied. It, too, is an inert and highly stable element (Table 3).

Since an unfilled valence shell is less stable than a filled valence shell, atoms with an incomplete outer shell have a strong tendency to interact with other atoms. They may gain, lose, or share enough electrons to complete their outermost shell. All the elements in living organisms have unfilled outermost shells (Table 4) and can therefore participate in chemical reactions with other atoms.

Some atoms with outer energy shells that are almost empty or almost full gain or lose electrons and form stable charged ions. For example, sodium has two electrons in its first energy shell, eight in its second energy shell, and only one valence electron in its third energy shell. This outermost single electron is weakly held and readily lost to another atom. The sodium atom is left with a completely filled outer shell, becoming a positively charged ion, Na^+. In contrast, chlorine has seven electrons in its outermost shell and readily accepts another electron to fill its outer shell completely and become a negatively charged ion, Cl^-.

Atoms can also become more stable when they share electrons in such a way that their valence orbitals are filled. This sharing of electrons in the valence shells of atoms creates what are called hybridized electron orbitals. In a hybridized electron orbital, there is a direct overlap of the valence electron orbitals of the two atoms, so the orbital is a combination of two different orbitals. Sharing electrons is the most common way for atoms to bond and form biological molecules. The sharing of electrons by C, H, O, and N underlies the formation of countless chemical bonds that hold biological molecules together.

Chemical Bonds

Atoms of inert elements, such as helium, neon, and argon, occur naturally in single-atom form. Atoms of reactive elements, however, combine with each other to form compounds. These atoms form a stable attraction to one another called a chemical bond. Four types of chemical bonds are important in biological molecules: ionic bonds, covalent bonds, and two types of intermolecular forces. You will learn about these bonds in this section. You will also learn about polar molecules, which influence how biological molecules interact.

Ionic Bonds

ionic bond a bond that results from the attraction between two oppositely charged atoms or molecules

cation an ion that has a positive charge

anion an ion that has a negative charge

An **ionic bond** forms between atoms that have lost or gained electrons to become charged (**Figure 4**). Atoms that have lost or gained electrons are called ions. Ions of opposite charge—one positive and the other negative—are strongly attracted to one another, and this attraction leads to an ionic bond. A positively charged ion is called a **cation**, and a negatively charged ion is called an **anion**. Ions are very strongly attracted to water molecules. As a result, ionic compounds tend to dissociate and dissolve in water, forming hydrated ions.

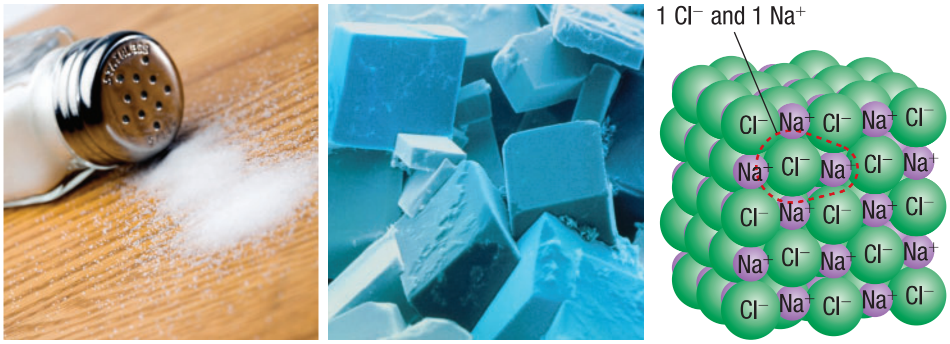


Figure 4 Sodium, Na, and chlorine, Cl, atoms form an ionic bond to become NaCl. The sodium atom loses an electron, and the chlorine atom gains an electron. Sodium chloride crystals are cubic in shape.

Covalent Bonds

Covalent bonds form when atoms share one or more pairs of valence electrons. The formation of molecular hydrogen, H_2, from two hydrogen atoms is the simplest example of the sharing mechanism (**Figure 5**). In H_2, two hydrogen atoms share two electrons and, as a result, both fill their valence electron shell. The strength of a covalent bond depends on the **electronegativity** of the atoms involved in the sharing of the electron pair. Electronegativity is the measure of an atom's attraction for additional electrons.

In molecular diagrams, a dash or a pair of dots represents a single pair of shared electrons in a covalent bond. For example, a molecule of hydrogen is represented as H–H or H:H. The number of covalent bonds that an atom can form is usually equal to the number of additional electrons needed to fill its valence shell. The shared orbitals that form covalent bonds extend between atoms at specific angles and directions, giving covalently bound molecules distinct three-dimensional forms.

A carbon atom has four electrons in its valence shell and can therefore bond with four hydrogen atoms to form the compound methane, CH_4 (**Figure 6**). Each hydrogen atom shares its one electron with the carbon atom, completely filling the carbon atom's valence shell. The carbon atom shares its four valence electrons with the four hydrogen atoms, completely filling the hydrogen atoms' valence shells. The bonds between the carbon atom and hydrogen atoms in the compound methane are arranged in four symmetrical orbitals, so the hydrogen atoms are 109.5° from each other. The overall arrangement of this molecule is tetrahedral. The number and tetrahedral arrangement of the bonds around a carbon atom allow carbon atoms to link together in more complicated biological compounds (**Table 5**).

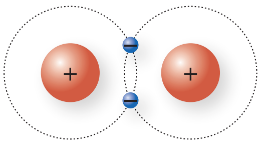
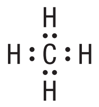


Figure 5 Covalent bond between two hydrogen atoms. The atoms share their electrons to fill the valence shell of each atom completely, creating a stable molecule of hydrogen, H_2.

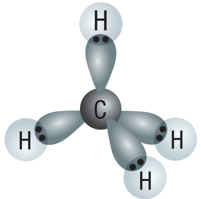
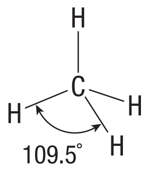
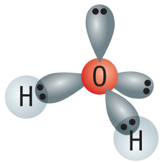
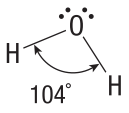
electronegativity the measure of an atom's attraction to shared electrons



$$\begin{array}{c} H \\ \ddot{} \\ H:C:H \\ \ddot{} \\ H \end{array}$$

Figure 6 Lewis dot diagram showing the structure of methane, CH_4

Table 5 Orbital and VSEPR models for Methane, Carbon Dioxide, and Water

Name and formula (shape)	Orbital model	VSEPR model	Bonding valence electron pairs	Non-bonding valence electron pairs
methane, CH_4 (tetrahedral)			4	0
water, H_20 (angular)			2	2

The electrons attempt to move as far away from one another as possible, creating an angle between the bonds. You can predict the arrangement of the bond angles around an atom using the valence shell electron pair repulsion (VSEPR) theory developed by Canadian chemist Ronald J. Gillespie. The VSEPR theory states that because electrons are negatively charged, valence electron pairs repel one another and move as far apart from one another as possible. For example, in a water molecule, there are two valence electron spaces available on the oxygen atom (Table 5). The valence electrons from two hydrogen atoms fill these spaces, forming the molecule H_2O. The VSEPR theory also takes into account non-bonding electron pairs of an atom. Oxygen has two electron pairs or four non-bonding electrons in its valence shell. The negative charge of these non-bonding electrons repels the pairs that make up the O–H bonds, so the O–H bonds arrange themselves at an angle of 104° from each other.

Polar Molecules

Although all covalent bonds involve the sharing of valence electrons, they differ widely in the degree of sharing that takes place. The more electronegative an atom is, the more strongly it attracts electrons. Electronegativity is influenced by the atomic number and the distance between the valence electrons and the nucleus of an atom. Electronegativity increases as the distance between the electrons and the nucleus decreases. Oxygen, for example, has a very high electronegativity because two additional electrons can occupy the valence orbitals that are very close to the oxygen's nucleus. In contrast, hydrogen is less electronegative because, although an additional electron can also get close to its nucleus, the very small size of the nucleus provides a much weaker force of attraction.

The unequal sharing of electrons between two atoms with different electronegativity results in a **polar covalent bond**. The difference in electronegativity between atoms in common bonds is shown in **Table 6**. Remember that most biological compounds contain carbon, hydrogen, and oxygen, and many also contain nitrogen. Due to their relatively high electronegativities, both oxygen and nitrogen form polar bonds with atoms of most other elements (**Table 7**). Carbon and hydrogen differ in electronegativity by only 0.4. Such a small difference results in bonds that can be considered non-polar.

polar covalent bond a bond between two atoms, made up of unequally shared electrons

Table 6 Electronegativity Differences of Selected Bonds

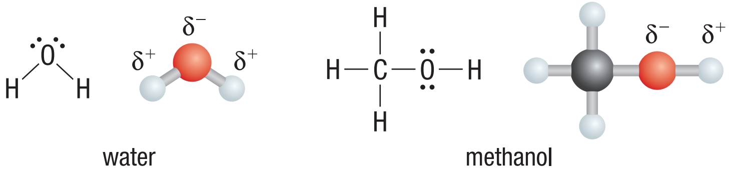
Bond	Electronegativity difference (ΔEN)
H—H	0.0
C—H	0.4
C—N	0.5
N—H	0.8
C—O	0.9
O—H	1.2

Table 7 Common Polar and Non-polar Bonds in Biological Molecules

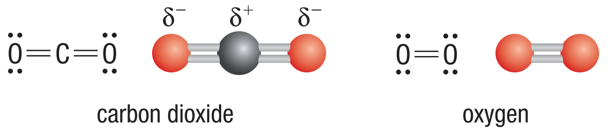
Polar bonds	Non-polar bonds
C—O	C—C
O—H	C═C
C═O	C—H
N—H	

The atom that attracts the valence electrons more strongly carries a partial negative charge, which results in the other atom carrying a partial positive charge. Because the atoms carry partial charges, the whole molecule may have a non-uniform charge distribution. This is the **polarity** of the molecule. For example, the oxygen atom in water forms a covalent bond with two hydrogen atoms. The oxygen atom attracts the shared electrons much more strongly than the hydrogen atoms (**Figure 7(a)**). Therefore, the bonds between oxygen and hydrogen are strongly polar. The more electronegative oxygen pulls the electrons closer, so the oxygen atom has a partial negative charge. Because the water molecule has an asymmetrical shape, with the oxygen atom positioned at a bend in the molecule, the partial charges on the atoms create an unequal distribution of charges on the molecule as a whole. In contrast, molecules such as carbon dioxide, CO_2, have an equal distribution of charges (**Figure 7(b)**). Carbon dioxide contains two double bonds with oxygen, making its three-dimensional arrangement appear linear. The bonds are polar, but the symmetry of the molecule results in a balanced distribution of the charges. Overall, the molecule is non-polar.

polarity partial positive or negative charge at the ends of a molecule



(a) polar molecules



(b) non-polar molecules

Figure 7 Comparison of (a) polar and (b) non-polar biological molecules. The lowercase Greek letter delta (δ) is used to indicate a partial charge. The symbol δ^+ indicates partially positive atoms, and the symbol δ^- indicates partially negative atoms.

Polar molecules attract and align themselves to other polar molecules and tend to be soluble in water. Polar molecules, including water molecules, tend to exclude non-polar molecules, such as oils and fats. As a result, non-polar molecules have very low solubility in polar liquids. **Figure 8** shows how a molecule of methanol will align itself with a water molecule. The partial negative charge of water's oxygen atom is attracted to the end of the methanol molecule that has a partial positive charge.

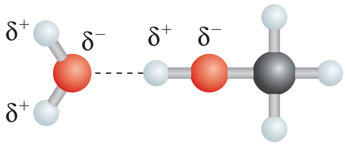


Figure 8 Methanol, CH_3OH, is pulled toward water molecules. The partial positive charge on the hydrogen atom in CH_3OH is pulled by the partial negative charge in the oxygen atom in water.

Intermolecular Forces

In addition to the intramolecular forces that exist within a molecule, there are forces of attraction between molecules, or **intermolecular forces**. Intermolecular forces are known as **van der Waals forces**. They are extremely important because they influence the physical properties, such as the solubility, melting point, and brittleness, of a substance. Van der Waals forces act between similar molecules, as well as between different types of molecules. The strength of these forces is dependent on the size, shape, and polarity of molecules.

intermolecular force the force of attraction between two molecules

van der Waals forces very weak attractions between two molecules, or parts of molecules, when they are close together

HYDROGEN BONDS

A hydrogen atom that is covalently bonded to a strongly electronegative atom in one molecule, such as oxygen or nitrogen, can become attracted to a strongly electronegative atom in a different molecule. The resulting attractive force is called a **hydrogen bond** (**Figure 9**). Hydrogen bonding is evident in the attraction of the hydrogen atom in CH_3OH and the partially negative oxygen atom in H_2O (Figure 8). Hydrogen bonds may form between atoms in the same or different molecules.

hydrogen bond the attractive force between a partially positively charged hydrogen atom and a partially negatively charged atom in another molecule

Hydrogen bonds are the strongest and most biologically significant form of van der Waals forces. Individual hydrogen bonds are weak compared with ionic and covalent bonds, but they can be very significant when they occur in large numbers. Although most of the strongest bonds in living organisms are covalent, weaker hydrogen bonds are crucial to the function of cells and cellular processes. The large size of biological molecules offers many opportunities for hydrogen bonding, both within and between molecules and with surrounding water molecules. A large number of hydrogen bonds are collectively strong, and they lend stability to the three-dimensional structure of large molecules, such as proteins.

The hydrogen bonds that exist between water molecules are responsible for many of the properties that make water a uniquely important molecule for all living organisms. Some of these properties include a very high heat capacity; high melting and boiling points; and cohesion, adhesion, and surface tension. Trees depend on cohesion to help transport water through xylem tissue up from their roots. The adhesion of water to the xylem cell walls of a plant helps to counteract the downward pull of gravity. Hydrogen bonds also give water an unusually high surface tension, causing it to behave as if it were coated with an invisible film (**Figure 10**).

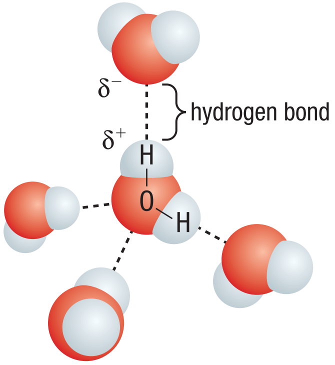


Figure 9 Each water molecule forms hydrogen bonds with up to four neighbouring molecules.

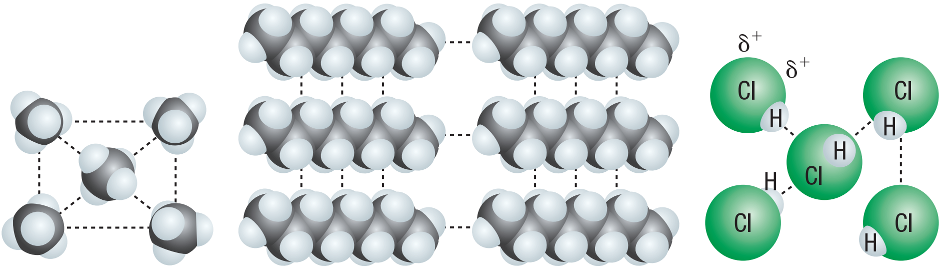
Figure 10 The hydrogen bonds in water give it an unusually high surface tension.

The weaker attractive force of hydrogen bonds makes them much easier to break than covalent or ionic bonds, especially when there is an increase in temperature, which increases the movement of the molecules. Hydrogen bonds begin to break extensively as temperatures rise above 45 °C. At 100 °C, hydrogen bonds in water are rapidly overcome.

OTHER VAN DER WAALS FORCES

Other van der Waal forces are even weaker and result from the momentary attractions of the electrons of one molecule to the nuclei of another molecule. These forces develop between all molecules, but they are only significant where other, stronger bonds are not prominent. Such is the case between non-polar molecules or between regions of slightly positive and slightly negative charges within a single molecule. Although an individual bond that has formed as a result of van der Waals forces is weak and transient, the formation of many bonds of this type can stabilize the shape of a large molecule, such as a fat.

The size and shape of a molecule influences the number and total strength of van der Waals forces of attraction. A larger molecule has larger forces of attraction. For example, small methane molecules, CH_4, are gases at room temperature because the very weak van der Waals forces are unable to hold the molecules together. In contrast, much larger non-polar octane molecules, C_8H_{18}, are liquid at room temperature because of the cumulative effect of many more van der Waals forces between the larger molecules (**Figure 11(a)** and **(b)**, next page). Also, linear molecules can align more easily with other molecules, and therefore the van der Waal forces are stronger. Polar molecules, such as hydrogen chloride, HCl, can also experience an attractive force between the positive and negative ends of the interacting molecules (**Figure 11(c)**). These influences of size and shape also apply to interactions that involve hydrogen bonds. The effect is very significant in long linear cellulose molecules, which have numerous OH functional groups and are able to form very strong solid fibres. Globular shaped molecules such as starches have fewer accessible atoms for van der Waals forces and therefore tend to form less rigid solids.



(a) methane, $CH_4(g)$ **(b)** octane, $C_8H_{18}(l)$ **(c)** hydrogen chloride, HCl

Figure 11 Non-polar molecules, such as (a) methane and (b) octane, can experience small attractive van der Waals forces, which hold the molecules together. (c) Polar molecules, such as hydrogen chloride, also experience van der Waals forces between their positively and negatively charged regions.

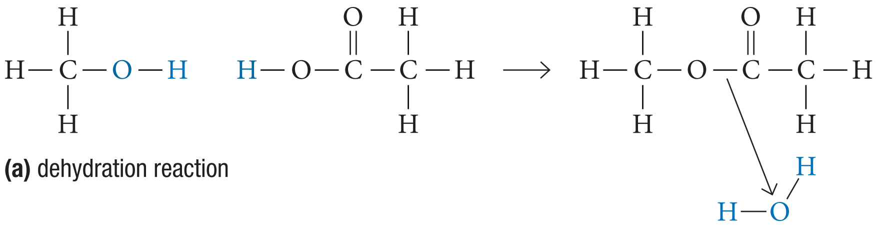
Chemical Reactions

Thousands of different chemical reactions occur inside cells, but they all have one thing in common. All chemical reactions involve the breaking and formation of chemical bonds, thereby changing the arrangements of atoms and ions. In the simple reaction between hydrogen gas, H_2, and oxygen gas, O_2, bonds within the molecules are broken and then new bonds are formed between oxygen and hydrogen to form water.

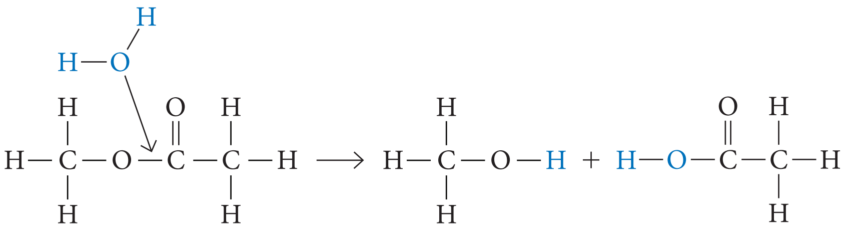
$$2\,H_2 + O_2 \rightarrow 2\,H_2O$$

dehydration reaction a chemical reaction in which subunits of a larger molecule are joined by the removal of water; also called a condensation reaction

There are four major types of chemical reactions that are common in biological processes: dehydration, hydrolysis, neutralization, and redox reactions. **Dehydration reactions** (also called condensation reactions) consist of the removal of an −OH and an −H from two reactant molecules. The −OH and −H form a water molecule, while the two reactant molecules are joined together (**Figure 12(a)**). Dehydration reactions are the most common method used by cells to join smaller molecules and assemble extremely large macromolecules, such as complex carbohydrates and proteins.



(a) dehydration reaction



(b) hydrolysis reaction

Figure 12 (a) Dehydration is the removal of –OH and –H from two reactant molecules to create water and a new bond. (b) Hydrolysis is the cleaving of a bond by the addition of water (as –OH and –H), splitting a larger molecule.

Hydrolysis reactions are the reverse of dehydration reactions. Water acts as a reactant to split or "lyse" a larger molecule. In living organisms, hydrolysis breaks down large molecules into smaller subunits. A bond in the reactant molecule is broken, and the –OH and –H from a split water are attached, resulting in two products (**Figure 12(b)**).

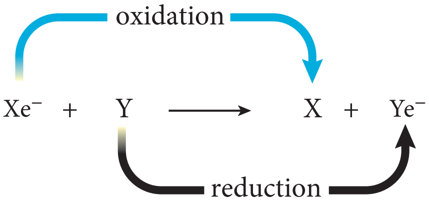
Neutralization reactions occur between acids and bases to produce salts. Water is also often produced in these reactions. An example of a neutralization reaction is the reaction between hydrochloric acid and sodium hydroxide. The products of these two reactants are water and sodium chloride (common table salt).

Redox reactions are the fourth type of chemical reaction. During a redox reaction (named for "reduction" and "oxidation"), electrons are lost from one atom and gained by another atom.

hydrolysis reaction a chemical reaction in which water is used as a reactant to split a larger molecule into smaller subunits

neutralization reaction a reaction in which an acid and a base combine to create a salt and water

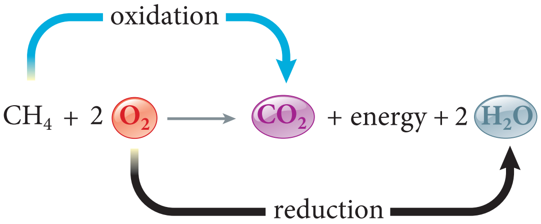
redox reaction an electron transfer reaction



As you will learn, entire atoms may be transferred during a redox reaction. The term **oxidation** refers to the loss of electrons. The result is an oxidized molecule or atom. The oxidation of one molecule is always linked to the reduction of another molecule. The term **reduction** refers to the gain of electrons. In a redox reaction, the oxidizing agent is the molecule or atom being reduced. The reducing agent is the molecule or atom being oxidized. Note that the term "oxidation" also refers to the transfer of entire hydrogen atoms (and their electrons) from less electronegative atoms to more electronegative atoms, as shown in the combustion of methane below.

oxidation a reaction in which a molecule loses electrons

reduction a reaction in which a molecule gains electrons



During oxidation reactions in biological systems, the electrons involved are more strongly attracted to the oxidizing agent. For example, during the oxidation of methane, CH_4, the electrons in the original C–H bonds are strongly attracted to oxygen. As the reaction proceeds, the weaker forces of attraction between the C and H atoms are overcome and the atoms separate. They are then pulled toward and form strong bonds with the oxygen atoms. The products now contain much stronger C=O bonds and O–H bonds, compared with the C–H bonds in methane. Thus, redox reactions involve electrons moving from where they are weakly held to where they are more strongly held. As you will learn in Chapter 3, redox reactions are responsible for most of the energy transfer within cells.

LEARNING **TIP**

Redox Reactions

A helpful pneumonic for remembering the roles of oxidation and reduction is "LEO the lion says GER":

Loss of Electrons = Oxidation

Gain of Electrons = Reduction

1.1 Review

Summary

- Isotopes are different forms of the same element, with different numbers of neutrons. A radioisotope is an unstable isotope that decays to release particles.
- Valence electrons are the electrons in the outermost electron shell of an atom.
- There are four types of chemical bonds in biochemistry: ionic, covalent, and hydrogen bonds, and weak van der Waals forces.
- Electronegativity is a measure of an atom's attraction for electrons. Differences in electronegativity result in bond polarity.
- Intermolecular forces are attractive forces between molecules.
- Dehydration is the removal of –OH and –H from two reactant molecules to form a larger molecule and water.
- Hydrolysis occurs when a bond in a large molecule is broken, and water is added to the resulting subunits.
- Oxidation is the loss of electrons, and reduction is the gain of electrons. The oxidation of one molecule or atom is always linked to the reduction of another molecule or atom. This is called a redox reaction.

Questions

1. One atom has 6 protons and a mass number of 13. Another atom has 6 protons and a mass number of 15. K/U
   (a) Identify each of the atoms.
   (b) Explain why there is a difference in the mass numbers.
2. (a) List the three common isotopes of hydrogen.
   (b) What are radioisotopes?
   (c) How are radioisotopes used in scientific research and medicine? K/U
3. An atom has eight electrons, and six of these electrons are valence electrons. K/U C
   (a) Draw an electron shell model for this atom. Which shells are occupied?
   (b) What is the name of the element?
4. How do bonding arrangements in a molecule affect the shape of the molecule? K/U
5. Compare ionic bonds with covalent bonds. K/U T/I
6. How can the atomic composition and shape of a molecule affect its polarity? K/U
7. (a) What effect do the polarity, size, and shape of a molecule have on the physical properties of the molecule?
   (b) How do these factors influence intermolecular forces? K/U T/I
8. How do polar covalent bonds and non-polar covalent bonds differ? K/U
9. In a bond between nitrogen and hydrogen (N—H), which atom will the electrons be closer to? Explain your reasoning. T/I
10. Oxygen plays a major role in biological molecules. Explain how oxygen plays a role in polarity, bond shape, and redox reactions. K/U
11. (a) In what ways do hydrogen bonds produce attractive forces between molecules? Include a labelled diagram to illustrate your answer.
    (b) How do hydrogen bonds influence the physical properties of water? T/I C
12. Describe dehydration and hydrolysis. How are these two types of reactions related? Draw a labelled diagram to support your answer. K/U C
13. (a) Describe reduction and oxidation.
    (b) Can a reduction reaction occur independently of an oxidation reaction, or vice versa? Why or why not? K/U

Water: Life's Solvent

1.2

Every time we feel thirsty, we are reminded about how much our bodies depend on water for survival. In fact, all living organisms depend on water. Up to 60 % of human body weight comes from water. About 70 % of the brain, 90 % of the lungs, and 22 % of bone tissue is water. Virtually all cellular processes occur in water, since cellular components are dissolved, suspended, and surrounded by water. Without water, we would not exist.

Water is a ubiquitous substance—all living organisms contain water, and many kinds of organisms live directly in water (**Figure 1**). It is both simple in its structure and complex in its functions. More substances dissolve in water than in any other liquid solvent. The reason for the excellent dissolving ability of water is related to its polarity. In this section, you will explore the properties of water. You will learn how it acts as the universal solvent and how it plays a role in so many chemical reactions.

Figure 1 Jellyfish are about 95 % water. They have one of the highest ratios of water content to body mass in the animal kingdom.

Properties of Water

Water is the most abundant liquid on Earth and is known as the "universal solvent." Water molecules are special because of their size, shape, polar structure, and ability to associate with each other through hydrogen bonding. Hydrogen bonds form readily between water molecules in both liquid water and ice. In liquid water, each water molecule forms an average of 3.4 hydrogen bonds with its neighbouring water molecules. This bonding forms an arrangement known as the water lattice (**Figure 2(a)**). The water lattice is a unique feature of water. Most molecules that are the size of water, such as H_2, O_2, CO_2, HCl, and H_2S, are gases at room temperature. In liquid water, the hydrogen bonds that hold the lattice together constantly break and reform, allowing water molecules to slip past one another and reform the lattice in new positions. This gives liquid water its fluid properties.

In ice, the water lattice is a rigid crystalline structure. Each water molecule in ice forms four hydrogen bonds with its neighbouring water molecules. The rigid ice water lattice spaces the water molecules farther apart than they are in the liquid water lattice (**Figure 2(b)**). Because of the greater spacing, water has the unusual property of being about 10 % less dense in its solid state than in its liquid state. Imagine what Earth would be like if ice sank to the bottom of oceans, lakes, and streams.

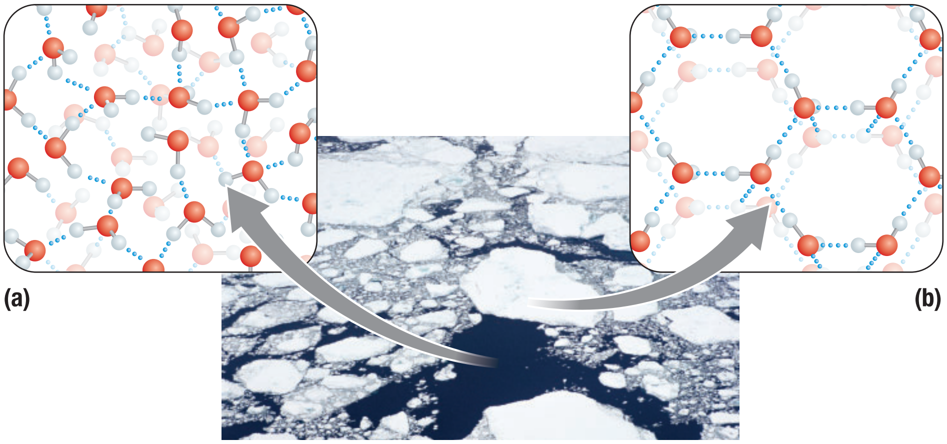


Figure 2 (a) Hydrogen bonding forms the liquid water lattice. Each water molecule makes an average of 3.4 bonds with its neighbours. (b) Hydrogen bonding forms the ice water lattice. Each water molecule bonds to four of its neighbours, creating a greater distance between the water molecules in ice.

As a result of its stabilizing hydrogen bond lattice, water has a high specific heat capacity. **Specific heat** is the amount of thermal energy that is required to increase the temperature of a given quantity of water by one degree Celsius. As thermal energy flows into a sample of water, much of it is absorbed by the process of breaking

specific heat the amount of thermal energy required to raise the temperature of a given quantity of a substance by 1 °C

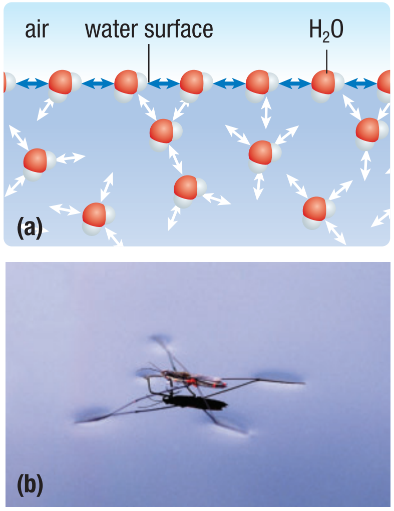


Figure 3 (a) The hydrogen bonding between water molecules creates surface tension. (b) The surface tension allows this water strider to walk on water.

hydrogen bonds. Therefore, the temperature of water increases relatively slowly as thermal energy is added. As a result, a lot of thermal energy and a relatively high temperature are needed to break enough bonds in water for it to boil. The high boiling point of water ensures that it is in a liquid state from 0 °C to 100 °C. Without its hydrogen bond lattice, water would boil at –81 °C. If the boiling point of water were –81 °C, most of the water on Earth would be in the gaseous state. We would not be able to drink it, swim in it, or have it inside our cells.

The hydrogen bond lattice of water results in water molecules staying close together—a property called cohesion. Surface tension is related to the concept of cohesion. Surface tension is the measure of how difficult it is to stretch or break the surface of a liquid (**Figure 3(a)**). Water molecules on the surface of a body of water can form hydrogen bonds on all sides, except the side that faces the air. This creates an imbalance in bonding, which produces a force that places the surface water molecules under tension and makes them more resistant to separation than the molecules below the surface. Surface tension is strong enough to allow small insects, such as water striders, to walk on water (**Figure 3(b)**).

Water molecules can also form hydrogen bonds with other polar molecules—a property called adhesion. For example, in a plant growing in soil, water moves in an unbroken column within microscopic conducting tubes of xylem tissue that extend from the roots of the plant to the highest leaves. Cohesion helps the water molecules stick together as they are transported up the xylem tubes, while adhesion helps the water molecules stick to the cell walls as they are transported. As water evaporates from leaves, water molecules move through the xylem tubes to replace the evaporated water. The unique properties of water are summarized in **Table 1**.

Table 1 The Unique Properties of Water

Characteristic	Property	Explanation	Effect	Example
Water clings.	cohesion	Water molecules form hydrogen bonds with each other.	high surface tension	• A water strider walks on the surface of a pond.
	adhesion	Water molecules form hydrogen bonds with other polar molecules.	capillary action and solubility of polar compounds	• Capillary action causes water to move up the xylem tubes in plants. • Polar substances, such as sugars, are highly soluble in water.
Water absorbs thermal energy.	high specific heat capacity	Hydrogen bonding causes water to absorb large amounts of thermal energy as its temperature increases, or lose large amounts of thermal energy as its temperature decreases.	temperature moderation	• High heat capacity helps organisms maintain a constant body temperature.
	high specific heat of vaporization	Hydrogen bonding causes liquid water to absorb large amounts of thermal energy and become a vapour (gas).	evaporation and cooling	• Many organisms, including humans, dissipate body heat by the evaporation of water from the surface of the body, often by sweating.
Solid water is less dense than liquid water.	highest density at 4 °C	As water molecules cool below 0 °C, they form an ice water lattice. The hydrogen bonds keep the water molecules spread apart, reducing the density so that it is below the density of liquid water.	ice floats on water	• Fish and other aquatic organisms survive in winter because water freezes from the top down. • Snow is a very good insulator. It provides protection from extreme cold for many organisms.

Aqueous Solutions

Water molecules are small and strongly polar—two qualities that allow them to readily surround polar and charged molecules and ions of other substances. The surface coat of water, called a hydration shell, reduces the attraction between the molecules or ions of another substance and promotes their separation. This separation allows the substance to go into solution. As the molecules and ions dissociate, water molecules surround them, forming the hydration shell. The hydration shell tends to prevent the ions from re-associating. The result is an aqueous (water-based) solution in which water is the solvent and the molecules or ions of the other substance are the solute.

A typical ionic substance is sodium chloride, commonly known as table salt. Sodium chloride dissociates in water because water molecules quickly form hydration shells around the Na^+ and Cl^- ions of the salt crystals (**Figure 4**). The surrounding water molecules reduce the attraction between ions so much that they separate from their normal crystal lattice structure and enter the surrounding water lattice as hydrated ions. This is why ionic substances or salts dissolve so easily in water. In much the same way, hydration shells surround macromolecules, such as sugars, nucleic acids, and proteins, that have ionic or polar regions on their surface. The surrounding water molecules act to reduce the electrostatic interaction between these macromolecules and other molecules. Polar molecules or charged ions that are strongly attracted to water are called **hydrophilic** (Greek for "water-loving") **molecules**. Non-polar molecules that are not strongly attracted to water are called **hydrophobic** (Greek for "water-fearing") **molecules**. Small and modest sized hydrophilic substances are highly soluble in water, while hydrophobic substances have very low solubility in water. As the solvent inside all our cells and in our blood, water dissolves thousands of solutes that are necessary for life. Because these substances are dissolved, they can float around and collide with each other, allowing chemical reactions to occur.

hydrophilic molecules polar or charged molecules that are strongly attracted to water

hydrophobic molecules non-polar molecules that are not strongly attracted to water

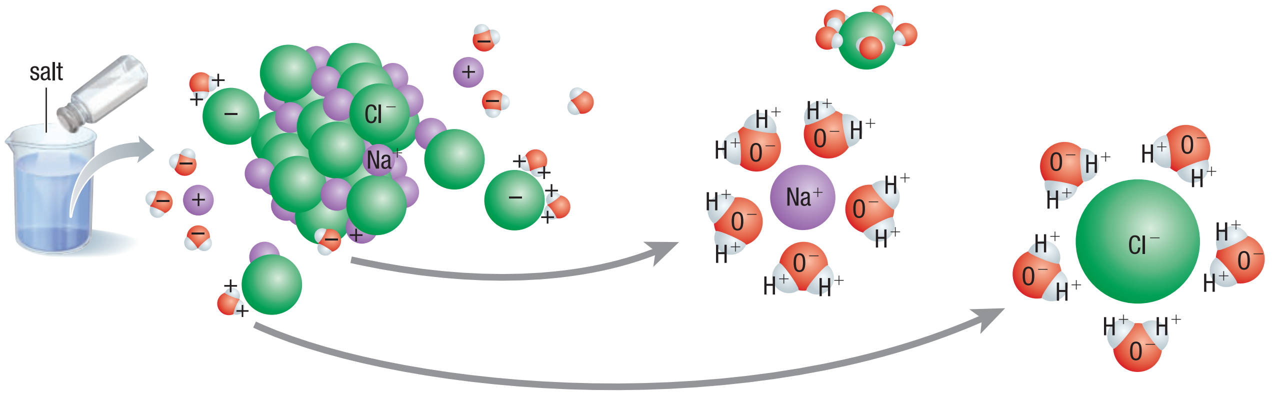


Figure 4 Salt dissolves in water. As water molecules surround Na^+ and Cl^- ions, they dissociate from one another and dissolve completely in the water.

Ionization and pH

Perhaps the most critical property of water, aside from its hydrogen bonding properties, is its ability to separate or dissociate into ions. Pure water is more than just H_2O molecules. Any given sample of water at 25 °C is a mixture of H_2O molecules, OH^- ions, and H_3O^+ ions. At this temperature, about two in every 550 million H_2O molecules react with each other. When two water molecules react, one water molecule transfers an H^+ ion to the other molecule, forming a hydronium ion, H_3O^+, and a hydroxide ion, OH^-. This process is called the **autoionization** of water (**Figure 5**). Autoionization always produces equal numbers of hydronium and hydroxide ions. Other dissolved substances, however, can alter this equal balance of ions.

autoionization the process in which a molecule spontaneously dissociates into ions

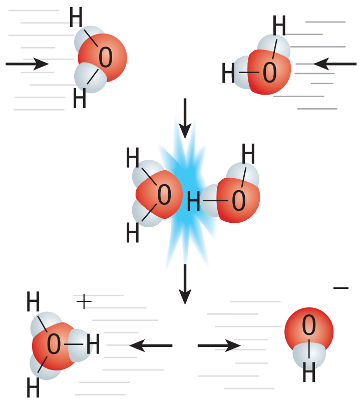


Figure 5 The autoionization of water

Acids and Bases

When the concentration of hydronium ions, H_3O^+, in a solution is greater than the concentration of hydroxide ions, OH^-, the solution has the properties of an acid. Acidic solutions are characterized by a sour taste, the ability to conduct electricity, and the ability to turn blue litmus paper red. Acids increase the hydronium ion concentration when dissolved in water and, in high enough concentrations, will cause a chemical burn. Acids contain at least one ionizable hydrogen ion in their chemical structure. The following equation shows the reaction of hydrogen chloride with water to produce hydrochloric acid:

$$\text{HCl (g)} + \text{H}_2\text{O (l)} \rightarrow \text{H}_3\text{O}^+ \text{(aq)} + \text{Cl}^- \text{(aq)}$$

When the concentration of OH^- ions in a solution is greater than the concentration of H_3O^+ ions, the solution has the properties of a base: a bitter taste and slippery feel, the ability to conduct electricity, and the ability to change red litmus paper blue. Bases increase the OH^- concentration of an aqueous (water-based) solution. In high enough concentrations, bases are caustic and will cause a painful chemical burn if brought in contact with the skin. The increase in OH^- ions is accomplished in one of two ways. Strong ionic bases, such as sodium hydroxide, may contain an OH group and thus dissociate when added to water, releasing OH^- ions:

$$\text{NaOH(s)} + \text{H}_2\text{O(l)} \rightarrow \text{Na}^+\text{(aq)} + \text{OH}^-\text{(aq)}$$

Other bases combine directly with H^+ ions. For example, ammonia, NH_3, which is a weak base and a product of decomposed plant matter, combines directly with an H_2O molecule. An H^+ ion from the water binds to ammonia, forming an ammonium ion, NH_4^+, and an OH^- ion:

$$\text{NH}_3\text{(g)} + \text{H}_2\text{O(l)} \rightarrow \text{NH}_4^+\text{(aq)} + \text{OH}^-\text{(aq)}$$

The concentration of H_3O^+ ions, compared to the concentration of OH^- ions, in an aqueous solution determines the acidity of the solution. Scientists measure the acidity of a solution using a numerical scale from 0 to 14, called the pH scale. The scale is based on logarithms to make the values more manageable:

$$\text{pH} = -\log_{10}[\text{H}^+]$$

where $[H^+]$ represents the concentration of H^+ or H_3O^+ ions in an aqueous solution.

Each whole number on the pH scale represents a 10-fold difference in pH. Therefore, a change of one pH number is actually a significant difference in acidity. In pure water, there is a balance of the concentrations of H_3O^+ and OH^- ions, so pure water is a neutral solution (neither acidic nor basic). The pH value assigned to a neutral solution is 7, since the concentration of H_3O^+ ions in pure water at 25 °C is 1.0×10^{-7} mol/L. Solutions with a pH that is less than 7 are considered to be acidic. Examples of acidic solutions are coffee, milk, and fruits such as oranges and tomatoes. Solutions with a pH that is greater than 7 are considered to be basic. Examples of basic solutions are hand soap, ammonia-containing solutions used for household cleaning, and egg whites (**Figure 6**).

Both the pH within cells and the pH of the external environment are important for the optimal functioning of life. A change of 0.1 or even 0.01 in the pH level of a cell can drastically affect biological reactions. A small change in the pH surrounding some proteins causes structural changes that can alter or destroy the functions of the proteins. Correct blood pH levels are essential for maintaining good health. The pH levels in the stomach are also critical for proper digestion and for defence against micro-organisms.

The pH of water in the environment is also critical for the survival of most organisms on Earth. The changing pH of freshwater bodies and oceans has a serious impact on ecosystems that depend on these water supplies for food or habitat. The pH of the oceans is about 8. The burning of fossil fuels is increasing atmospheric concentrations of carbon dioxide, which in turn is resulting in an increase in carbon dioxide entering oceans and fresh water. As more carbon dioxide is absorbed by ocean water, the water and the carbon dioxide form carbonic acid, and the water becomes more acidic. Scientists are becoming alarmed by the potential impacts of these processes. Increasingly acidic ocean water is harming many marine organisms and ecosystems, including coral reefs, and ultimately threatens the health of Earth's oceans.

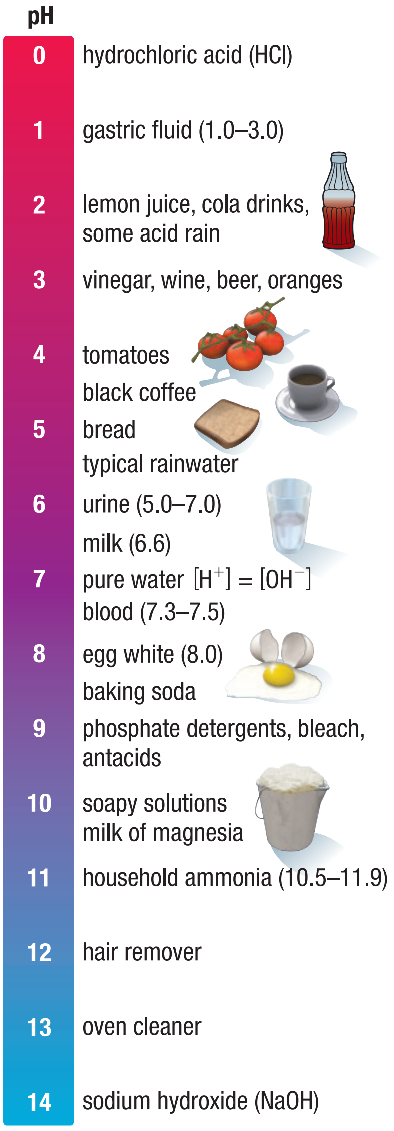

pH
0 hydrochloric acid (HCl)
1 gastric fluid (1.0–3.0)
2 lemon juice, cola drinks, some acid rain
3 vinegar, wine, beer, oranges
4 tomatoes
black coffee
5 bread
typical rainwater
6 urine (5.0–7.0)
milk (6.6)
7 pure water [H+] = [OH−]
blood (7.3–7.5)
8 egg white (8.0)
baking soda
9 phosphate detergents, bleach, antacids
10 soapy solutions
milk of magnesia
11 household ammonia (10.5–11.9)
12 hair remover
13 oven cleaner
14 sodium hydroxide (NaOH)

Figure 6 The pH values of common substances

Strong and Weak Acids and Bases

Acids and bases can be classified as strong or weak. The strength of an acid or base depends on the degree to which it ionizes when dissolved in water. A strong acid, such as HCl, and a strong base, such as NaOH, are completely dissociated in an aqueous solution. This means that all the molecules of HCl release H^+ ions that interact with water to form H_3O^+, and all the OH^- ions are released from NaOH and increase the hydroxide ion concentration of the water in which they are dissolved. Conversely, a weak acid and a weak base only partially ionize in water. For example, only 10 % of ammonia, a weak base, forms ammonium ions in water. Similarly, only 1.3 % of acetic acid, CH_3COOH, a weak acid, dissociates in water:

$$CH_3COOH + H_2O \leftrightarrow CH_3COO^- + H_3O^+$$

Thus, 98.7 % of the CH_3COOH stays together.

The reaction of a weak acid or a weak base in water is a reversible reaction. This means that the molecules can dissociate in water to form a weak acid or base, and the ions can re-associate once in solution. For example, when first placed in water, acetic acid molecules begin to form hydronium and acetate ions. At this point, the forward reaction is favoured. As the concentration of these ions in solution increases, the reverse reaction occurs more frequently. When about 1.3 % of the acetic acid molecules have ionized, equilibrium is reached. The forward and backward reaction rates are the same, so the concentrations of all the entities of the solution remain constant. Most acids and bases that are involved in biochemical reactions are weak.

Neutralization Reactions and Buffers

Water has a neutral pH value of 7. It is neither an acid nor a base. However, when an acid and a base react with one another, the products of the reaction include water and salt. This type of reaction is called a neutralization reaction, since its products, water and salt, are neutral. For example, when the acid HCl and the base NaOH react with one another in solution, the products that are formed are water and a salt, sodium chloride:

$$HCl\ (aq) + NaOH\ (aq) \rightarrow H_2O\ (l) + NaCl\ (aq)$$

Living organisms have some control over the internal pH of their cells by using buffers. A **buffer** is a chemical that compensates for relatively small pH changes by absorbing or releasing hydrogen ions. When a biological reaction releases excess H^+ ions, buffers combine with the H^+ ions so they are no longer free in the solution. Conversely, if the concentration of H^+ ions in a solution decreases, buffers can release H^+ ions into the solution to increase their concentration. Since weak acids and bases dissociate in a reversible reaction in water, most buffers are weak acids, weak bases, or a combination of the two. These buffers release or absorb H^+ and OH^- as necessary.

buffer a chemical that compensates for pH changes in a solution by accepting or donating H^+ ions

The buffering mechanism that helps to maintain a healthy blood pH in the narrow range of 7.35 to 7.45 is a good example of how buffers work in your body. In humans and many other animals, a buffering system that is based on carbonic acid, H_2CO_3, which is a weak acid, helps to maintain proper blood pH levels. In water solutions, carbonic acid dissociates readily into bicarbonate ions, HCO_3^-, and H^+. Like dissociation reactions in weak acids, this dissociation reaction is reversible:

$$H_2CO_3 \rightarrow HCO_3^- + H^+ \quad \text{or} \quad H^+ + HCO_3^- \rightarrow H_2CO_3$$

Therefore, if there is a very large number of hydrogen atoms in a solution, these atoms will collide frequently with the bicarbonate ions. As a result, the second reaction (the reverse reaction) will occur more frequently, and the H^+ ions will be absorbed as carbonic acid molecules form. Conversely, if there are very few H^+ ions in solution, they will not collide as frequently with the bicarbonate ions, and the reverse reaction will occur at a slower rate than the forward reaction (the first equation above). The forward reaction is favoured, and this causes the release of more H^+ ions. These back and forth adjustments of the buffer system help to keep human blood within its normal pH range.

1.2 Review

Summary

- Water forms a lattice structure through hydrogen bonding in liquid water and ice.
- The hydrogen bonding of water molecules to one another gives water a high surface tension.
- As polar molecules or charged ions dissolve in solution, they are completely surrounded by water molecules, which reduce the electrostatic interactions between them.
- The proper pH of cells inside living organisms and their environment is critical for the survival of the organisms.
- Strong acids and bases dissociate completely in water. Weak acids and bases dissociate only partially in water. Acids and bases react to form water and a salt in neutralization reactions.
- A buffer is a weak acid or base that can compensate for changes in a solution to maintain the proper pH level.

Questions

1. Water is a polar molecule. Explain how the polarity of water accounts for its lattice structure. K/U
2. How does the structure of water account for its properties, such as its boiling point, surface tension, and adhesion? K/U
3. Potassium bromide, KBr, is an ionic compound. Describe what happens to its ions when it is dissolved in water. K/U
4. Will water form a surface coat around a molecule such as octane, $CH_3(CH_2)_6CH_3$ (**Figure 7**)? Explain. K/U

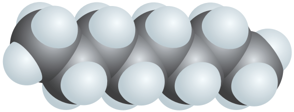


Figure 7

5. How does polarity influence water's role as a solvent? K/U
6. How do acids and bases differ in terms of how they behave when added to pure water? K/U T/I
7. What determines whether an acid or a base is classified as strong or weak? Explain your answer. K/U
8. Why is it important that we help to maintain the proper pH of our environment? Make a connection between the proper pH of our environment and your life and surroundings. K/U A
9. How do buffers in your cells help to keep your body functioning properly? K/U
10. Why would it be inaccurate to say that a buffer is a solution that maintains a constant pH? K/U
11. Vitamin C is also known by its chemical name, ascorbic acid. T/I
    (a) What does this name suggest about its chemical and physical properties?
    (b) Which of these properties might you notice if you ate some pure vitamin C?
12. Ants belong to the family Formicidae, named after their ability to release formic acid (**Figure 8**). Do online research to find out why ants produce formic acid. What other well-known insects produce formic acid? T/I

Figure 8

WEB LINK

The Carbon Chemistry of Life 1.3

Carbon atoms make up the base of every organic molecule, including the molecules within cells. Carbon is unparalleled in the biological world in its ability to form the backbone of large diverse molecules. This unique role arises from carbon's bonding properties—carbon can assemble into an astounding variety of chain and ring structures. Carbon has four electrons in its valence shell, and therefore each carbon atom is capable of forming four covalent bonds with other atoms. As a result, carbon is able to form such substances as multi-ringed molecules, diamonds, and nanotubes. Each carbon atom is a connecting point from which a molecule can branch out, in up to four directions. With combinations of single, double, and triple bonds, an almost limitless array of molecules is possible.

Carbon Chains: The Backbone of Biochemistry

As well as forming bonds with other atoms (chiefly hydrogen, nitrogen, oxygen, and sulfur), carbon atoms bind to each other to form long chains, rings, or branched structures. Molecules consisting only of carbon atoms bonded to hydrogen atoms are called hydrocarbons. The smallest hydrocarbon is methane. Methane is a single carbon atom bound to four hydrogen atoms (**Figure 1(a)**). Since carbon always has four bonds, if a carbon atom is bound to two other carbon atoms, the remaining bonds are available to bond to hydrogen, an additional carbon, or other elements (**Figure 1(b)**).

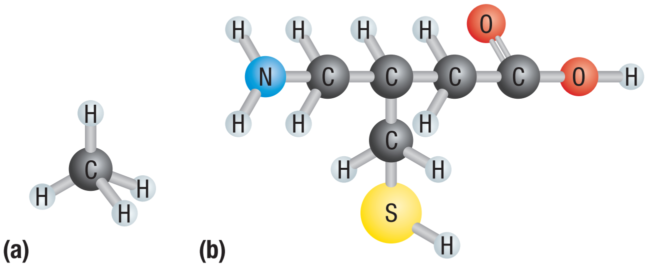


Figure 1 (a) Methane is the simplest hydrocarbon. It consists of 1 carbon atom bound to 4 hydrogen atoms. (b) Carbon atoms can form chains that branch.

The chain of carbon atoms in a biochemical molecule is the carbon skeleton of the molecule. Carbon skeletons can be linear or branched or form a closed ring shape, as in cyclohexane, C_6H_{12} (**Figure 2**). Many carbon-containing rings can join to produce polymers, such as the string of sugar molecules that make up a complex sugar chain.

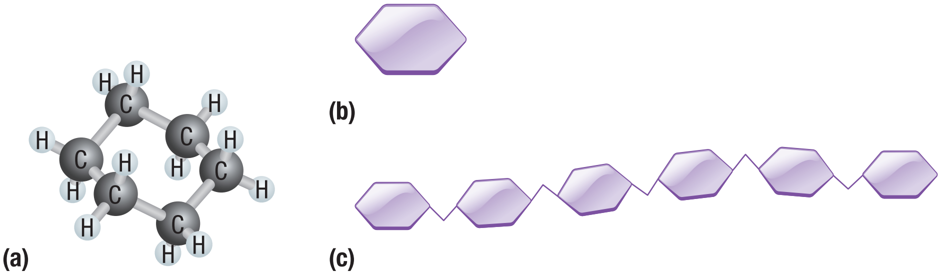


Figure 2 (a) The ring structure of cyclohexane is formed by 6 carbon atoms and 12 hydrogen atoms. (b) The hexagon symbol is frequently used for a carbon ring. (c) Carbon rings may contain an oxygen atom at one corner and can be joined into a chain.

Double or triple bonds can form between two carbon atoms, decreasing the number of remaining bonding sites by one or two, respectively (**Figure 3**). There is almost no limit to the number of different hydrocarbon structures that are possible, but they are rarely used by living organisms. Instead, the molecules of living organisms almost invariably contain other elements in addition to C and H. These other elements give the biological molecules different functional properties. These molecules fall into four major groups, based on their function: carbohydrates, lipids (fats), proteins, and nucleic acids.

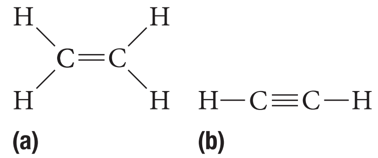


Figure 3 (a) A double bond forms between two carbons, decreasing the number of bonds that can form with other atoms by one. (b) A triple bond can form between two carbon atoms, decreasing the available binding sites by two for each carbon.

Functional Groups

Carbohydrates, lipids, proteins, and nucleic acids undergo synthesis and degradation in living organisms through interactions between small reactive groups of atoms that are, themselves, part of these large biochemical molecules. These small reactive groups are called **functional groups** (**Figure 4**). Unlike non-polar hydrocarbon chains, functional groups are usually ionic or strongly polar. Functional groups on large molecules interact with other molecules and introduce different types of bonding.

functional group a group of atoms that affects the function of a molecule by participating in chemical reactions

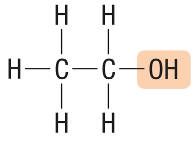
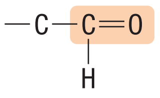
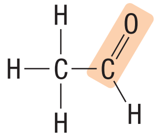
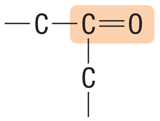
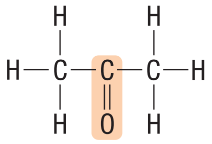
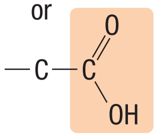
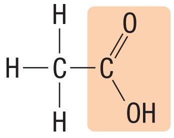
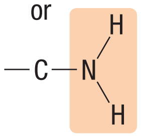
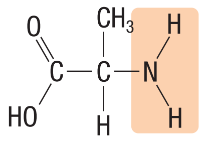
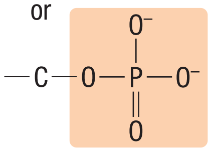
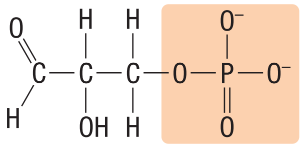
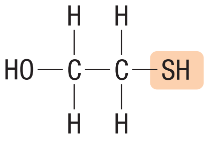
Functional group	Major classes of molecule	Example
hydroxyl —C—OH	alcohols	 ethyl alcohol (in alcoholic beverages)
carbonyl 	aldehydes	 acetaldehyde
	ketones	 acetone (a solvent)
carboxyl —C—COOH or 	organic acids	 acetic acid (in vinegar)
amino —C—NH_2 or 	amino acids	 alanine (an amino acid)
phosphate —C—PO_4^{2-} or 	nucleotides, nucleic acids, many other cellular molecules	 glyceraldehyde-3-phosphate (product of photosynthesis)
sulfhydryl —C—SH	many cellular molecules	 mercaptoethanol

Figure 4 Common functional groups in biological molecules

Characteristics of Functional Groups

Most functional groups are either ionic or strongly polar. This makes them very attracted to other ionic or polar molecules, including water molecules. Therefore, the chemical or physical properties of a large biological molecule are influenced by the polar and ionic characteristics of its functional groups. The forces of attraction that are created by ionic and polar groups are necessary in a chemical reaction in order to form new bonds. The non-polar portions of a large biological molecule do not attract other molecules. Therefore, they do not help to initiate chemical reactions.

Polar groups often act as "handles" on a large molecule. For example, some polar functional groups are strongly attracted to water and therefore can often be dissolved in the cytosol of the cell. The comparison of ethane, CH_3CH_3, and ethanol, CH_3CH_2OH, gives an example of how polar functional groups can influence the physical and chemical properties of a molecule. Ethane, a hydrocarbon, has no functional group and is non-polar. Although it has a lot of potential energy and could make a great fuel, ethane is a gas at room temperature and is not soluble in water. In comparison, ethanol has an alcohol functional group (—OH), which gives it polar characteristics. It is a liquid at room temperature and highly soluble in water. Ethanol's high solubility

UNIT TASK **BOOKMARK**

Consider what you are learning about the structure and function of functional groups as you work on your Unit Task (p. 108). How can this information help you understand your molecule?

means that it can be dissolved in the cell cytosol, where it can be used as a fuel, providing energy for the cell. Ethane has slightly higher energy content than ethanol, but it has no value as a fuel for most living organisms since it is lacking a polar group that would make it soluble in their cytosol.

The carboxyl, amino, and phosphate groups are ionic functional groups (**Figure 5**). The carboxyl group, COOH, can release a proton to become COO^-. The release of H^+ in water makes the carboxyl group an acid. The amino group, NH_2, can attract and bond to an H^+ proton to become an NH_3^+ group. This characteristic makes the amino group a weak base. When you study proteins, you will learn that they are made of amino acids. As the name implies, an amino acid has both an acid (carboxyl) and a base (amino) as functional groups. Phosphate functional groups are also acidic. These groups lose their H^+ ions and become negatively charged. DNA, or deoxyribonucleic acid, is an acid because it contains a huge number of these phosphate groups along the backbone of its structure. For this reason, the overall charge of DNA is negative.

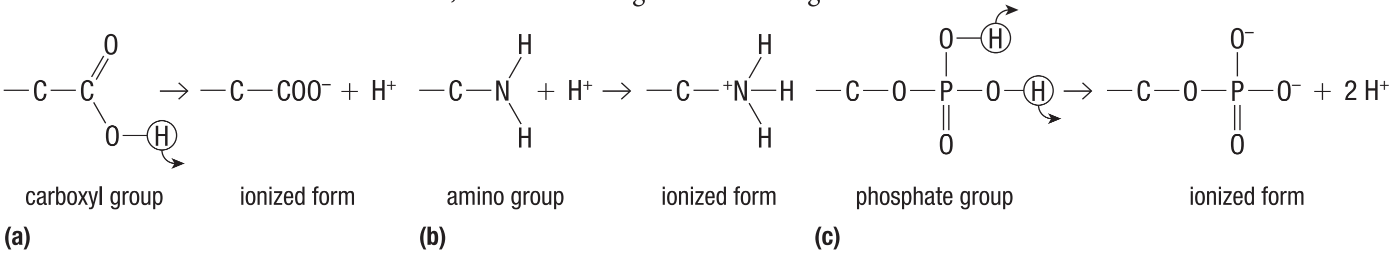


Figure 5 Ionic functional groups: (a) The carboxyl group acts like an acid, releasing H^+ ions to become negatively charged. (b) The amino group acts like a base, accepting H^+ ions to become positively charged. (c) The phosphate group acts like an acid, releasing H^+ ions to become negatively charged.

Dehydration and Hydrolysis Reactions

In many reactions, functional groups lose or gain an H^+ or OH^-, the components of water, as they interact with other molecules. As you learned in Section 1.1, dehydration removes components of a water molecule, usually during the assembly of a larger molecule from smaller subunits. An example of a dehydration reaction occurs when individual sugar molecules combine to form a starch molecule, which is a larger macromolecule (**Figure 6(a)**). Two —OH groups interact with each other during dehydration, with the oxygen atom in one group attracted to the hydrogen atom in the other group. Water forms during this reaction. The remaining oxygen atom forms a bridge as it bonds the two subunits together to form a larger molecular compound.

The reverse process of dehydration is hydrolysis. In this process, the components of a water molecule, H^+ and OH^-, are added to functional groups as the molecules break into smaller subunits. For example, the breakdown of starch into individual sugars occurs by hydrolysis (**Figure 6(b)**). Note that two hydroxyl groups are formed when water is added to the oxygen bridge in this hydrolysis reaction, and these hydroxyl groups can interact with each other. Hydrolysis and dehydration reactions are among the most important reactions in cells. Both the assembly and breakdown of large biological molecules depend on these reactions.

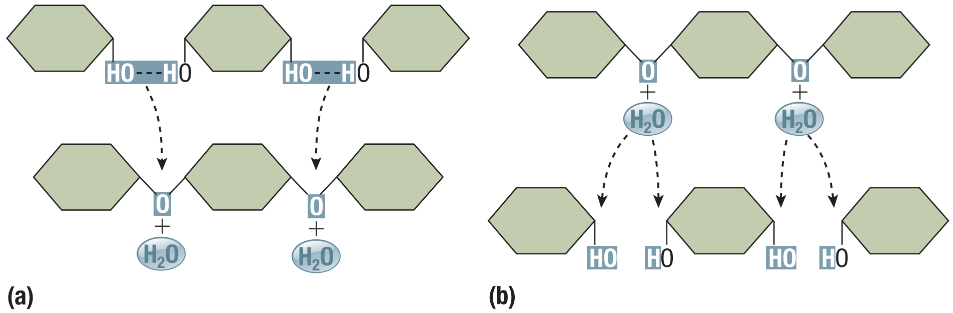


Figure 6 (a) During dehydration, water is produced as subunits join to form larger molecules. (b) During hydrolysis, water is used as a reactant to split larger molecules into smaller subunits.

1.3 Review

Summary

- Carbon atoms form the backbone of biological molecules. They can link together to form chains, branched structures, and rings.
- Functional groups have polar or ionic qualities that influence how they interact with water and other molecules.
- During a dehydration reaction, water is removed from subunits as they combine to form a larger molecule.
- During a hydrolysis reaction, larger molecules react with water and break down into smaller subunits.

Questions

1. Explain how the electron arrangement in carbon atoms enables them to form straight and branching chains and ring structures. K/U T/I
2. What is the primary purpose of the functional groups that are found in organic molecules? K/U
3. Considering the functional groups you have studied, why do you think that compounds with similar structures often have similar uses? K/U A
4. Explain how functional groups influence solubility and the forces of attraction between molecules. K/U
5. What role does oxygen play in most functional groups? T/I
6. Using a balanced chemical equation, show how each of the following functional groups changes in an aqueous solution. K/U T/I
   (a) carboxyl group
   (b) amino group
   (c) phosphate group
7. Draw an example of a dehydration reaction and a hydrolysis reaction. Explain your examples to a classmate. K/U C
8. Compare and contrast dehydration synthesis and hydrolysis. K/U
9. Is the following reaction an example of dehydration synthesis or hydrolysis? Explain your answer. K/U

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$$

10. When would a cell use the dehydration and hydrolysis reactions of polysaccharides? K/U T/I
11. Investigate some of the properties and uses of one of the major classes of functional groups shown in Figure 4 (page 26). Write a paragraph describing them. T/I
12. Examine each of the following molecules. T/I C
    (a) Identify the functional group on the molecule (**Figures** 7 and **8**).

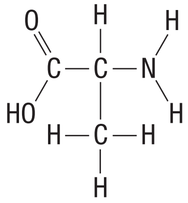


Figure 7

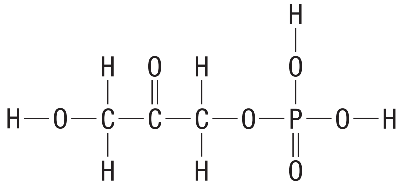


Figure 8

    (b) How will each functional group influence the solubility and/or acidity of the molecule?
    (c) Research these molecules. Write a paragraph to describe how they are used by living cells.

WEB LINK

Carbohydrates and Lipids

Although carbohydrates and lipids can be quite large, they are relatively simple biochemical molecules. They are composed mostly of carbon, hydrogen, and oxygen, arranged in a variety of configurations. Although simple in structure, however, they perform many complex functions in cells. Carbohydrates and lipids are best known for their role as energy sources in the body, yet they are much more than this (**Figure 1**). Carbohydrates play a role in structural support and cell-to-cell communication. They are the raw material that is used to build other important molecules, such as amino acids, lipids, and nucleic acids. Lipids also play an important structural role in cells—all biological membranes are composed of lipid molecules. As well, hormones, certain vitamins, and defence mechanisms are based on lipids. Lipids provide insulation for nerve cells and have waterproofing qualities. The functional groups on carbohydrates and lipids influence their properties and functions. CAREER LINK

Figure 1 Bees produce honey, a carbohydrate, and store it in hives constructed from waxes, a type of lipid.

Carbohydrates

Carbohydrates, or simple and complex sugar molecules, are among the most common biological molecules on Earth. The term "carbohydrate" comes from the terms *carbo*, meaning carbon, and *hydrate*, meaning water. In photosynthesizing plants and other photosynthesizing organisms, carbon dioxide and water molecules are used as raw materials to build carbohydrates. Plants and algae produce millions of tonnes of carbohydrates each year. These and other organisms use carbohydrates as an energy source, as a building material, and for cell communication. Carbohydrates are in the foods you eat, including fruits, vegetables, and grains. Nutritionists study the composition of food and determine the amounts of carbohydrates that are present in the different foods we eat. CAREER LINK

carbohydrate a biomolecule that consists of carbon, oxygen, and hydrogen

Monosaccharides

The simplest type of carbohydrate is called a **monosaccharide**, because it contains a single sugar. Monosaccharides generally have a combination of carbon, hydrogen, and oxygen atoms in the ratio of 1 carbon : 2 hydrogen : 1 oxygen. This is represented by the chemical formula $(CH_2O)_n$, or its derivative $C_nH_{2n}O_n$, where n is the number of carbon atoms. Carbohydrates appear either as monosaccharides or as two or more monosaccharide units linked together. Glucose is perhaps the most widely used monosaccharide. Plants produce glucose during photosynthesis, and it provides energy for countless functions in both plants and animals.

monosaccharide the simplest form of carbohydrate, consisting of a single sugar unit; a building block for more complex carbohydrates

Monosaccharides that contain three carbons (triose), five carbons (pentose), and six carbons (hexose) are the most common in living organisms (**Figure 2(a)**, next page). Although all monosaccharides can occur in a linear form, when formed in water, monosaccharides with five or more carbon atoms fold back on themselves to form a ring. Folding into a ring occurs through a reaction between two functional groups in the same monosaccharide. This can be seen in the monosaccharide glucose, when the carbonyl group interacts with a hydroxyl group to form a ring (**Figure 2(b)**, next page). Carbon atoms in the glucose molecule have numbers assigned to them. Scientists use these numbers when discussing the structures of sugars.

When glucose forms a ring, there are two possible arrangements of the –OH group, which is bound to the carbon at position 1: α-glucose and β-glucose (**Figure 2(c)**, next page). These two different forms of glucose are isomers. An **isomer** is a molecule that has the same chemical formula as another, but a different arrangement of the atoms. The different arrangements of the –OH group on glucose can give chemicals different properties. For example, humans can easily digest starches composed of α-glucose. However, cellulose, assembled from β-glucose, is completely indigestible for humans. Glucose, fructose, and galactose are isomers of each other.

isomer a molecule that has the same composition as another, but a different arrangement of atoms

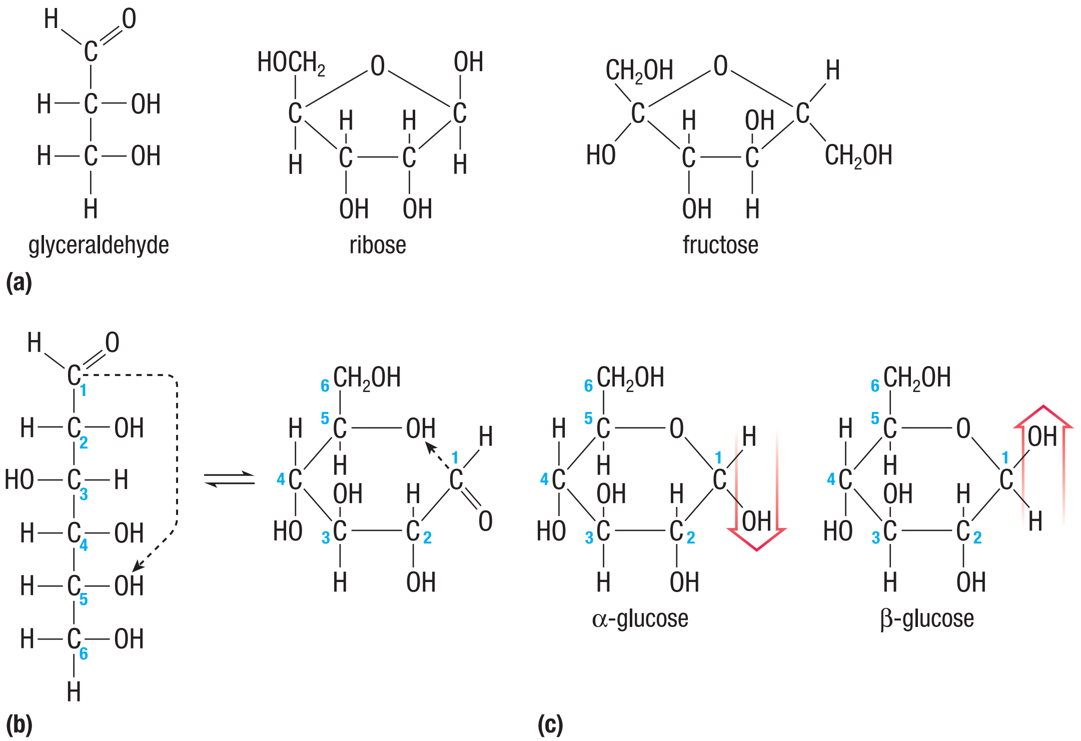


Figure 2 Common monosaccharides are (a) glyceraldehyde, ribose sugar, and fructose sugar. (b) Glucose forms a ring structure due to the interaction of two of its functional groups. (c) There are two possible arrangements of the —OH group on carbon 1 in glucose: α-glucose and β-glucose.

Sugars typically have many polar functional groups attached to them. This makes them very hydrophilic and means that small sugars are highly soluble in water. The sweet taste that is associated with carbohydrates requires them to be dissolved in water. Monosaccharides are the sweetest. As the number of monosaccharide units that are linked together increases, the sweetness decreases.

Disaccharides

disaccharide a carbohydrate molecule that is made from two monosaccharide units

glycosidic bond a bond between two monosaccharides

Disaccharides consist of two monosaccharides that are joined together by a dehydration synthesis reaction (Section 1.3). For example, the disaccharide maltose forms through the linkage of two α-glucose molecules, with oxygen as a bridge between the 1-carbon of one glucose unit and the 4-carbon of the second glucose unit (**Figure 3(a)**, next page). Bonds of this type, which link monosaccharides into larger carbohydrates, are called **glycosidic bonds.** A glycosidic bond forms between α-glucose and fructose monosaccharide, resulting in the disaccharide sucrose (**Figure 3(b)**, next page). Lactose, the disaccharide milk sugar, forms when galactose and β-glucose bond together (**Figure 3(c)**, next page). The chemical shorthand for representing a glycosidic bond between a 1-carbon and a 4-carbon is 1→ 4. Other linkages, such as 1→ 2, 1→ 3, and 1→ 6, are also common in carbohydrate chains. Linkages are designated as α or β, depending on the orientation of the —OH group bonded to the 1-carbon. The linkage in maltose and sucrose is an α-linkage, but the linkage in lactose is a β-linkage.

Disaccharide carbohydrate molecules contain the same functional groups that make monosaccharides hydrophilic. Therefore, they are easily dissolved in water. Maple syrup, produced from the sap of maple trees, consists mostly of sucrose molecules dissolved in water (**Figure 4**). Maple syrup is a sugar source that was first used by Aboriginal people. In the spring, they collected maple sap and boiled it into syrup. Using the knowledge obtained from the Aboriginal people, European settlers learned to use maple syrup as a sweetener. Québec is now the world's largest producer of maple syrup. Other major sources of sucrose (table sugar) are sugar cane and sugar beets.

Figure 4 Sap from a sugar maple tree consists of sucrose molecules dissolved in water.

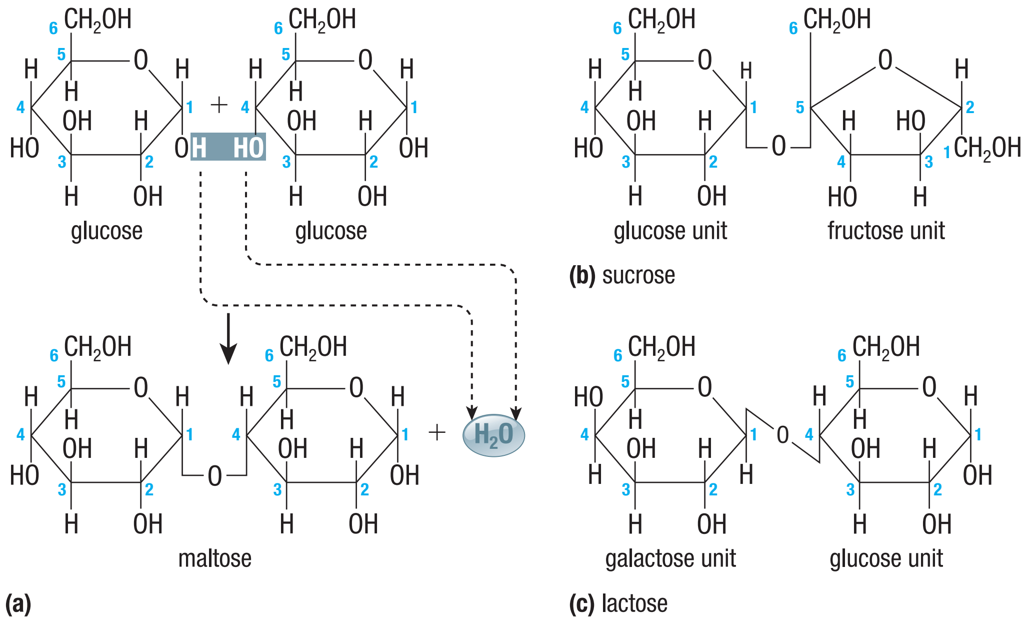


Figure 3 (a) A glycosidic bond between the 1-carbon and 4-carbon atoms of two glucose molecules creates maltose. (b) Sucrose has an α-linkage. (c) Lactose has a β-linkage.

Complex Carbohydrates: Polysaccharides

Hundreds to thousands of monosaccharides can link together to form a **complex carbohydrate**. Some complex carbohydrates are important for energy storage in cells, while others are essential for structural support. Starch and glycogen are examples of storage carbohydrates, and cellulose and chitin are examples of structural complex carbohydrates.

complex carbohydrate a molecule that is composed of hundreds to thousands of monosaccharides linked together; an essential part of nutrition and a valuable energy source

POLYSACCHARIDES

A **polysaccharide molecule** is a chain of monosaccharides with many subunits joined by glycosidic linkages (**Figure 5**, next page). A polysaccharide is a macromolecule, which is a very large molecule assembled by the covalent linkage of smaller subunit molecules. The dehydration synthesis reactions that assemble polysaccharides are examples of polymerization. **Polymerization** is the process in which identical or variable subunits, called **monomers**, link together in a long chain to form a larger molecule. This molecule is called a **polymer**, hence the term "polymerization." The linkage of non-identical subunits creates highly diverse and varied biological molecules. Many kinds of polymers are found in cells, not just polysaccharides. For example, DNA is another type of polymer.

polysaccharide molecule a molecule that contains many linked monosaccharides

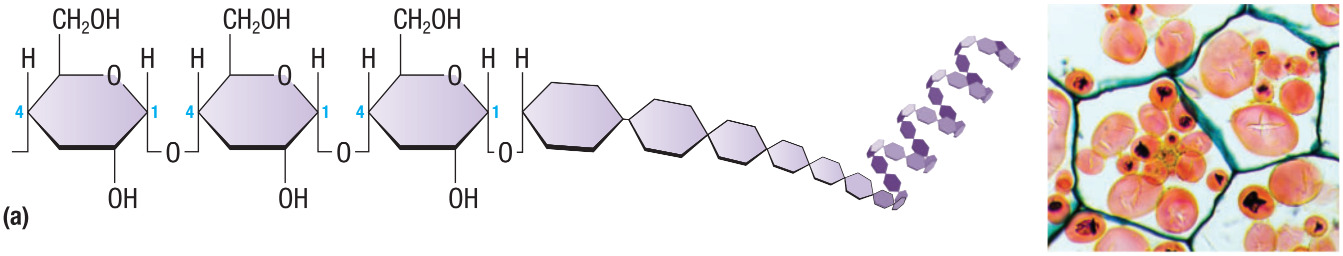
polymerization a process in which small subunits are linked to form a large molecule

monomer a small molecule that can bind chemically to other molecules

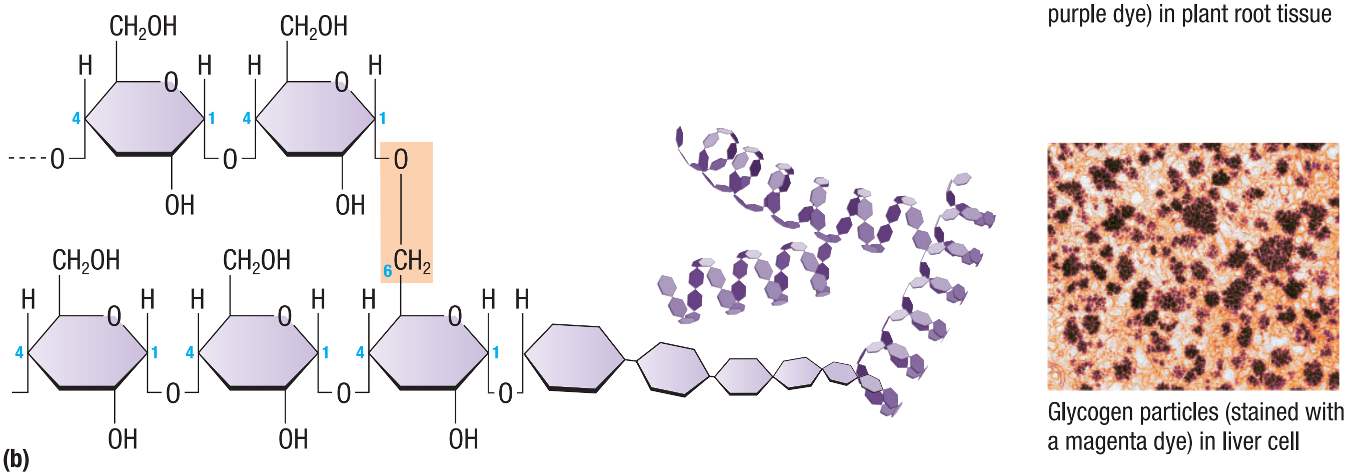
polymer a large molecule that is formed when monomers link together chemically in a chain

The most common polysaccharides are plant starches, glycogen, and cellulose. They assemble from hundreds or thousands of glucose units. Cellulose is the main component of plant cell walls and the most abundant organic molecule on Earth. Cellulose molecules are long and straight and have very large numbers of polar OH groups. These two features enable many cellulose molecules to assemble side by side and form hundreds or thousands of hydrogen bonds. These numerous hydrogen bonds are what give cellulose fibres their great strength. Other polysaccharides form from a variety of different sugar monomers. Polysaccharides may be linear unbranched molecules, or they may contain branches in which side chains of sugar units attach to a main chain.

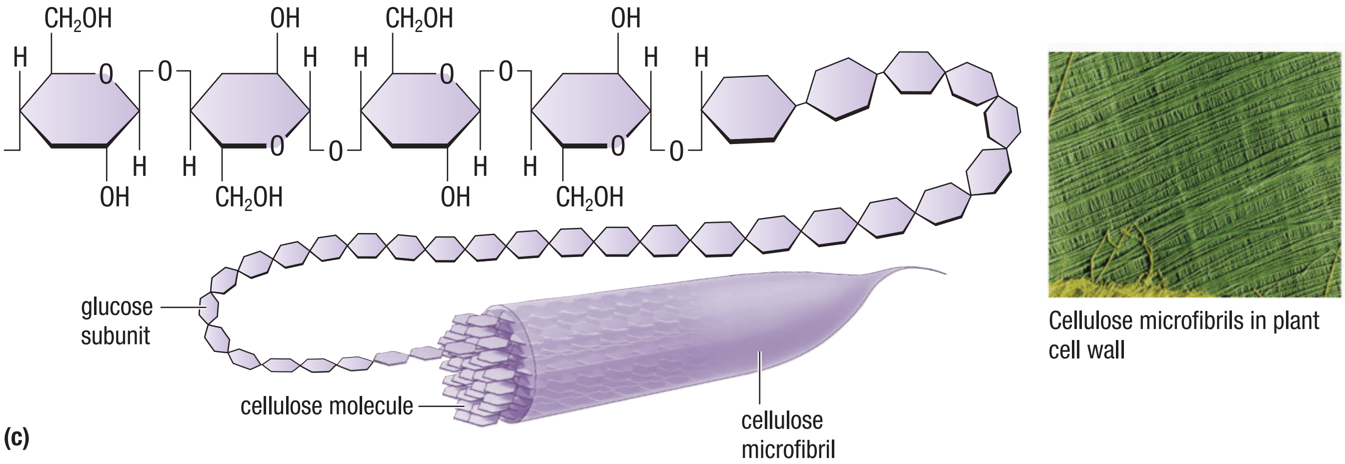
Polysaccharides are very polar and therefore very hydrophilic. However, since polysaccharides are such huge molecules, they attract water but cannot dissolve. This is the principle behind absorbent paper towels. Paper towels are made of cellulose, a long fibrous polysaccharide. Paper towels attract water, but they do not dissolve in the water. If they did, they would not be useful for cleaning up spills. **Table 1** (page 33) is a summary of the different types of carbohydrate molecules.



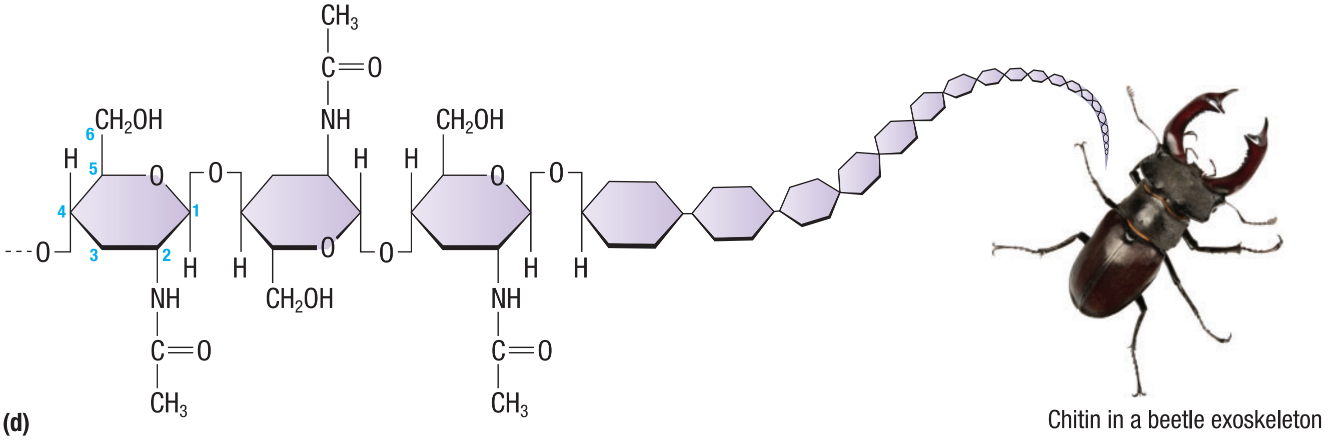
Amylose grains (stained with a purple dye) in plant root tissue



Glycogen particles (stained with a magenta dye) in liver cell



Cellulose microfibrils in plant cell wall



Chitin in a beetle exoskeleton

Figure 5 Examples of polysaccharides and their structure. (a) Amylose is the soluble component of starch. (b) Glycogen is used for energy storage in animals. (c) Cellulose is the main component of plant cell walls. It is the most abundant organic molecule on Earth. (d) Chitin is used by insects and crustaceans to produce hard exoskeleton. It is also a component of fungal cell walls. Chitin is one of the few carbohydrates that contain functional groups with nitrogen atoms.

Table 1 Structures and Functions of Carbohydrates

Type	Structure	Function	Example
monosaccharide	chain, α-ring, or β-ring	energy source, building blocks	glucose, ribose, and deoxyribose
disaccharide	two monomer subunits, with α or β linkage	energy source	sucrose, maltose, and lactose
polysaccharide	very long chain or branching chain with α or β linkages	energy storage, structural support, and cell-to-cell communication	starch and cellulose

Mini **Investigation**

Modelling Carbohydrates

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this investigation, you will build and observe three-dimensional models of simple carbohydrates to understand how they are assembled into larger units.

Equipment and Materials: chemical modelling kit

1. With a partner, use the chemical modelling kit to construct a model of α-glucose and a model of fructose.
2. Perform a dehydration synthesis reaction to form a sucrose disaccharide.
3. Perform a hydrolysis reaction to re-form the two monosaccharides.
4. Rearrange the atoms in fructose to change it into glucose.
5. Convert both glucose molecules to their β forms. Link them using a dehydration reaction.
6. Link your two β-glucose disaccharides with another group's β-glucose disaccharides.

A. What is the waste product of the dehydration synthesis reaction? T/I

B. What is the overall chemical formula of each of the three molecules you created? Determine the C:H:O ratio for the monosaccharides. T/I

C. How are fructose and glucose similar? How do they differ? Are they isomers? T/I

D. What large polysaccharide is similar to the glucose chain you created? What other polysaccharide could you have formed if the glucose molecules had been in their α form? T/I

E. Observe the number of OH groups on these molecules. What can the number of —OH bonds tell you about the molecule and its relationship with water? How does the —OH group influence solubility? T/I

Lipids

The term **lipid** is a general term for a variety of non-polar biological molecules. Lipids are composed mostly of hydrogen, carbon, and lesser amounts of oxygen. They are smaller than complex carbohydrates, so they are not considered to be macromolecules, and they are not polymers of defined monomeric subunits. Since lipids are generally non-polar, they do not dissolve in water. Their insolubility in water contributes to their ability to form cell membranes. Lipids have other functions as well. Some lipids are stored by cells, to be used as an energy source (**Figure 6**). Other lipids serve as hormones that regulate cellular activities and as vitamins. Lipids in living organisms fall into five main categories: fatty acids, fats, phospholipids, steroids, and waxes.

lipid a non-polar compound that is made mostly of carbon and hydrogen

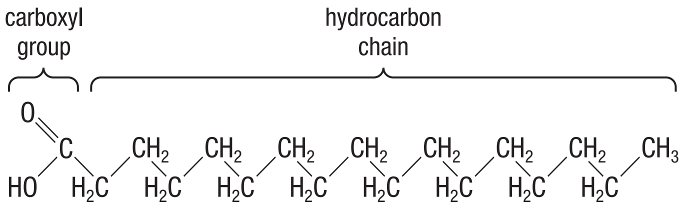
Figure 6 As penguins dive into extremely cold water, a layer of fat under their skin acts as thermal insulation.

Fatty Acids

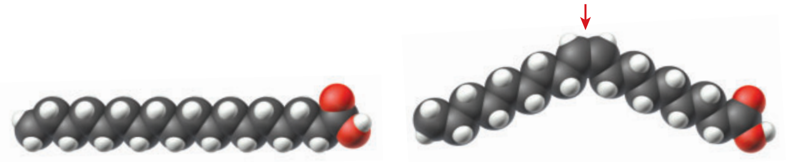
The structural backbone of most lipids is derived from fatty acids. A **fatty acid** consists of a single hydrocarbon chain with a carboxyl functional group (—COOH) at one end (**Figure 7(a)**, next page). The carboxyl group gives the fatty acid its acidic properties. Fatty acids in living organisms contain four or more carbons in their hydrocarbon chain. The most common forms of fatty acids have even-numbered chains of 14 to 22 carbons. As their chain length increases, fatty acids become progressively less water soluble.

fatty acid a molecule that consists of a carboxyl group and a hydrocarbon chain

If the hydrocarbon chain of a fatty acid binds the maximum possible number of hydrogen atoms, and if all the carbons are linked to each other with single bonds, the fatty acid is said to be saturated (**Figure 7(b)**). If there are double bonds in the fatty acid chain, then it is said to be unsaturated. This means that the carbon chain has the potential to form more bonds with hydrogen (**Figure 7(c)**). Fatty acids with one double bond are monounsaturated, and those with more than one double bond are polyunsaturated. The presence of a double bond in an unsaturated fatty acid creates a kink in the molecule, which causes it to bend.



(a) fatty acid



(b) stearic acid, $CH_3(CH_2)_{16}COOH$ **(c)** oleic acid, $CH_3(CH_2)_7CH{=}CH(CH_2)_7COOH$

Figure 7 (a) A fatty acid consists of a carboxyl group attached to a long hydrocarbon chain. (b) Stearic acid is a saturated fatty acid. (c) Oleic acid is an unsaturated fatty acid.

Fats

triglyceride a fat; three fatty acid chains linked to a glycerol molecule

A fat is a lipid that is made from two types of molecules: fatty acid and a glycerol molecule. In a fat molecule, one to three fatty acid chains are joined to a single glycerol molecule through dehydration synthesis between –OH functional groups on the glycerol and carboxyl functional groups on the fatty acids. **Triglycerides** are the most well-known fats. They contain three fatty acid chains (**Figure 8**). A fat molecule can have identical fatty acid chains, or different fatty acid chains, linked to glycerol.

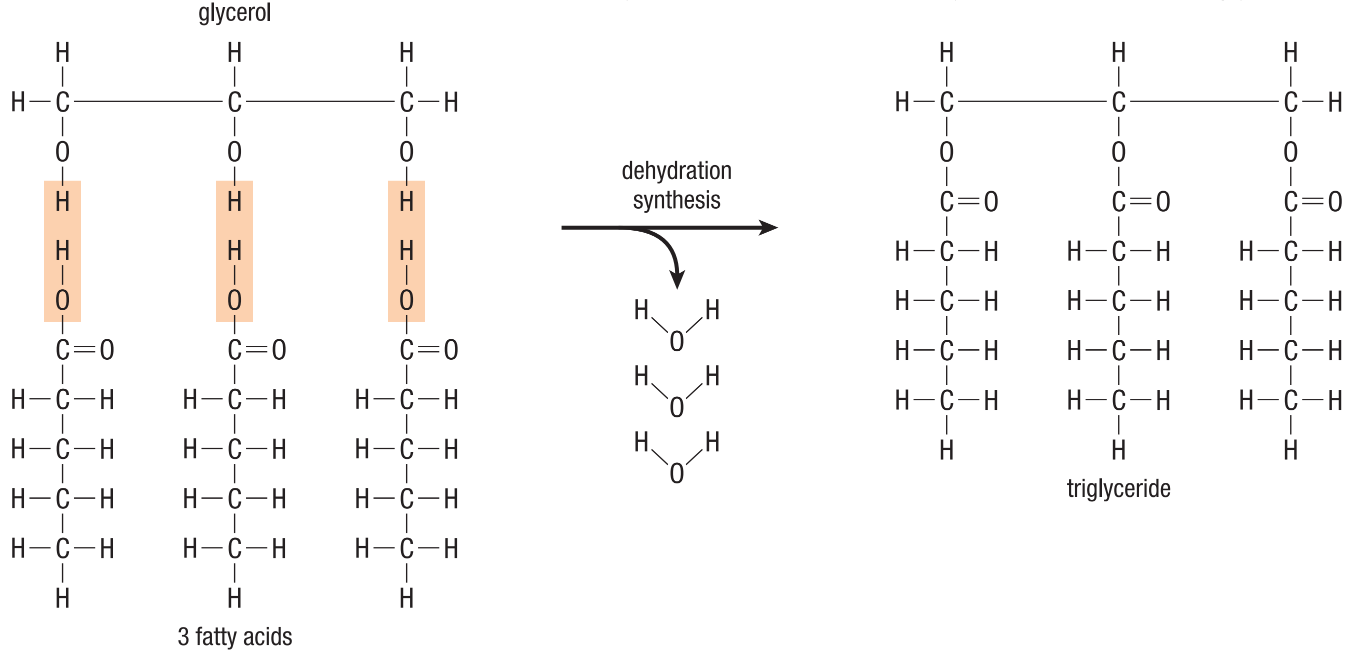


Figure 8 A triglyceride forming from one glycerol and three fatty acid molecules in a dehydration synthesis reaction

Different organisms usually have distinctive combinations of fatty acids in their triglycerides. For example, fats obtained from animals, such as butter and lard, usually contain only saturated fatty acids, so they are called **saturated fats**. Fats derived from plants, such as olive oil, usually contain more unsaturated and polyunsaturated fatty acids, so they are called **unsaturated fats**. Unsaturated fats are generally referred to as oils. Like individual fatty acids, triglycerides generally become less fluid as the length of their fatty acid chain increases. Those with shorter chains remain liquid, as oils, at room temperature. The more saturated fats, such as butter, are solids because their chains are long and straight and can be packed closely together to form a solid structure at room temperature. Fatty acid chains that have kinks are bent and cannot be packed as tightly as saturated fats, Therefore, these molecules stay more fluid and are liquid at room temperature.

Living organisms need flexible cells so they can move around easily. If large amounts of fat in animals were solid, it would be difficult for animals to move about. Warm-blooded mammals and birds are the exception in having mostly saturated fats, but these fats are liquids because of relatively high body temperature. Many plant seeds contain mostly unsaturated fats, which are liquids even at lower temperatures. Cold-water fish need their bodies to stay flexible at lower temperatures, so the fats in their bodies are mostly unsaturated fish "oils." This is one of the benefits of eating fish.

Triglycerides function widely as stored energy. Gram for gram, they yield more than twice as much energy as carbohydrates. Therefore, fats are an excellent source of energy in a diet. Storing the equivalent amount of energy as carbohydrates rather than fats would add more than 45 kg to the average person. A layer of fatty tissue just under the skin serves as insulation in mammals and birds.

Most plant fats are unsaturated fats, which are generally considered healthier than saturated animal fats for the human diet. Diets rich in saturated fats can lead to heart disease, whereas diets rich in unsaturated fats can improve your health. The Inuit, who live in the Arctic, depend on a diet that is very high in animal proteins from fish, seal, whales, caribou, and waterfowl. Their diet is high in both fat and protein, but very low in carbohydrates. The high fat (high energy) content is beneficial for living in such a cold climate. Most of the fats in their diet are made of monounsaturated and omega-3 fatty acids. Therefore, the fat they eat is healthier fat than the saturated animal fats in a typical North American diet.

Phospholipids

Cells could not exist without the phosphate-containing lipids called **phospholipids**. Phospholipids are the primary lipids of cell membranes. In the most common phospholipids, as in triglycerides, glycerol forms the backbone of the molecules. Only two of its binding sites, however, link to fatty acids. The third site links to a charged phosphate group, which often binds to another polar or charged unit (**Figure 9**). Thus, a phospholipid contains two hydrophobic fatty acids at one end, attached to a hydrophilic polar group, often called the head group (**Figure 10(a)** and **(b)**, next page). Molecules that contain both hydrophobic and hydrophilic regions are called amphipathic molecules. The head of an amphipathic molecule is the polar and hydrophilic region. The tail is the hydrophobic lipid, which is composed of a carbon chain.

Phospholipids make up the lipid bilayer of cell membranes, an important structural feature of cells. The hydrophilic end of a phospholipid faces outward toward water, and the hydrophobic fatty acid tails face inward toward each other (**Figure 10(c)**, next page).

saturated fat a lipid that is composed of saturated fatty acids with single bonds in their hydrocarbon chain

unsaturated fat a lipid that is composed of unsaturated fatty acids with double bonds in their hydrocarbon chain

phospholipid a lipid that consists of two fatty acids and a phosphate group bound to glycerol

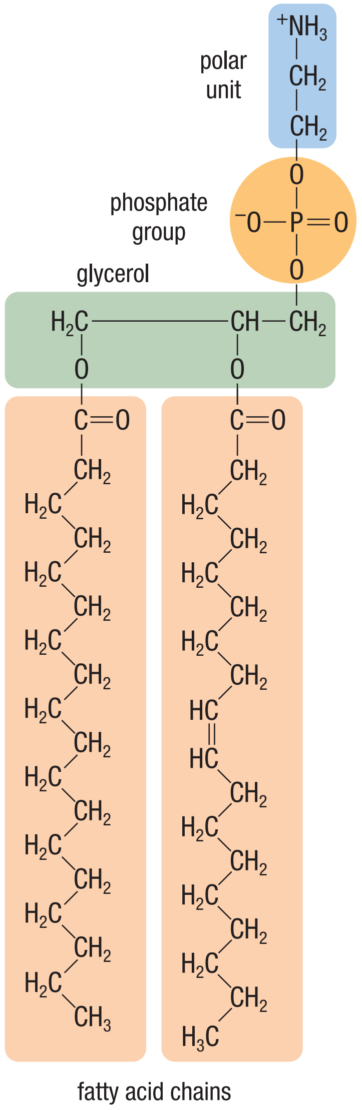


Figure 9 A phospholipid has a polar end and a non-polar end. The non-polar end consists of glycerol bonded to two fatty acids. Phosphattidyl ethanolamine is an example of a phospholipid.

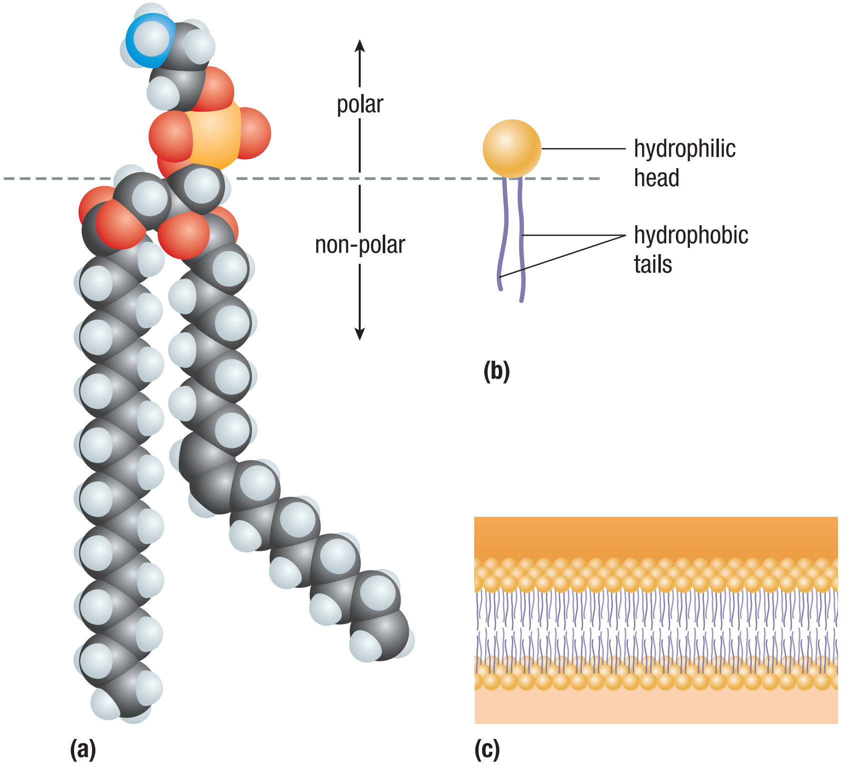


Figure 10 (a) This structural model of a phospholipid shows the polar and non-polar ends. (b) A phospholipid has a hydrophilic head and two hydrophobic tails. (c) A phospholipid bilayer forms the basic structure of a cell membrane.

Steroids

Steroids are a group of lipids with structures that are based on a framework of four fused carbon rings. Small differences in the side groups that are attached to the rings distinguish one steroid from another. The most abundant steroids, the sterols, have a single polar –OH group at one end of the ring framework and a complex, non-polar hydrocarbon chain at the other end. Although sterols are almost completely hydrophobic, the single hydroxyl group gives one end a slightly polar, hydrophilic character. As a result, sterols also have dual solubility properties and, like phospholipids, tend to assume positions in cells that satisfy these properties. Cholesterol, a steroid, is an important component of the plasma membrane that surrounds animal cells. Similar sterols, called phytosterols, occur in plant cell membranes.

Cholesterol is a steroid that is essential for animal cell membranes and converts into a number of compounds, such as vitamin D. Too much dietary cholesterol, however, can be harmful to your body. A high concentration of cholesterol in the bloodstream and a diet rich in saturated fats have been linked to the development of atherosclerosis, a condition in which fat deposits, or plaques, form on the inner lining of blood vessels. This blocks the flow of blood to tissues, which often leads to a heart attack.

Sex hormones, such as testosterone, estrogens, and progesterone, are also steroids (**Figure 11**). They control the development of sexual traits and sex cells that are specific to males and females. Anabolic steroids, which are used by some athletes to build muscle mass, mimic the male sex hormone testosterone. The use of anabolic steroids is banned by all major sporting bodies, yet some athletes still use them to gain an advantage over their competitors. Anabolic steroids have many harmful effects on the body, including high blood pressure, depression, suicidal tendencies, changes in the levels of the sex hormones, and, in young people, reduced growth.

steroid a lipid that is composed of four carbon rings

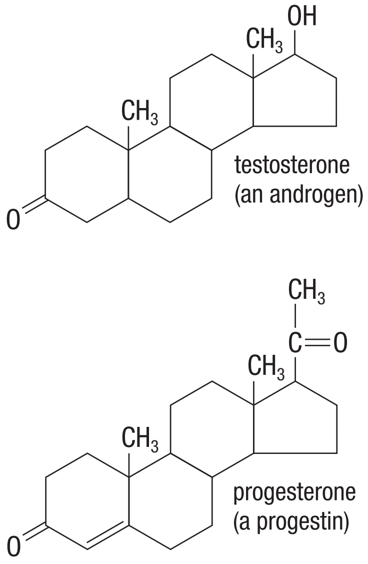


Figure 11 The sex hormones testosterone and progesterone belong to the sterol family of lipids. Notice their similar four-carbon ring structure.

Waxes

Waxes are large lipid molecules that are made of long fatty acid chains linked to alcohols or carbon rings. Waxes are hydrophobic, extremely non-polar, and soft solids over a wide range of temperatures. These characteristics are what make them ideal for flexible waterproof coatings on various plant and animal parts. One type of wax, cutin, is produced by certain plant cells to form a water-resistant coating on the surfaces of stems, leaves, and fruit (**Figure 12**). Cutin enables plants to conserve water, and it acts as a barrier to infections and diseases. Such functions are vital for life. Without this waxy coating, plants could not survive on land. Birds secrete a waxy material that helps to keep their feathers dry. Bees produce beeswax to make their honeycombs. **Table 2** is a summary of the different types of lipid molecules.

wax a lipid that is formed when long fatty acid chains are joined to alcohols or carbon rings

Table 2 Structure and Function of Lipids

Type	Structure	Function	Example
fatty acid	carboxyl group linked to a hydrocarbon chain	cellular functions and energy storage	stearic acid
fat	three fatty acid chains linked to glycerol	energy storage and insulation	butter and olive oil
phospholipid	two fatty acid chains and one phosphate group linked to glycerol	cell membrane	lipid bilayer
steroid	four carbon rings	hormonal signalling, cell response to the environment, and growth	testosterone and cholesterol
wax	long fatty acid chains linked to alcohol or carbon rings	water resistance and protection	wax coating on fruits, leaves, and stems

Figure 12 Cutin, a wax, is produced by the fruits, leaves, and stems of plants to create a waterproof barrier.

Mini **Investigation**

Modelling Lipids

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this investigation, you will build and observe three-dimensional models of simple lipids.

Equipment and Materials: chemical modelling kit

1. In pairs, use the chemical modelling kit to construct a model of glycerol and three short fatty acids: a four-carbon saturated fatty acid, a four-carbon unsaturated fatty acid, and a five-carbon saturated fatty acid.
2. Perform three dehydration synthesis reactions to produce a triglyceride.
3. Perform hydrolysis reactions to re-form the individual components.
4. Research the structure of one steroid of your choosing, and build the steroid.

A. Which functional groups are involved in the dehydration synthesis reactions in Step 2? What are the waste products in this reaction? T/I

B. What is the overall chemical formula of the triglyceride? T/I

C. What is the C:H:O ratio in the triglyceride you synthesized? T/I

D. How does the C:H:O ratio in triglycerides compare with the overall C:H:O ratio in carbohydrates? T/I

E. Which element is less abundant in fats? T/I

F. Compare the polarity of the molecules before and after the formation of the triglyceride. T/I

G. Compare the overall acidity of the molecules before and after the formation of the triglyceride. T/I

H. Compare the steroid that your group built with the steroids that other groups built. Can you identify the steroids that the other groups built? How are the steroids similar? How are they different? T/I C

WEB LINK

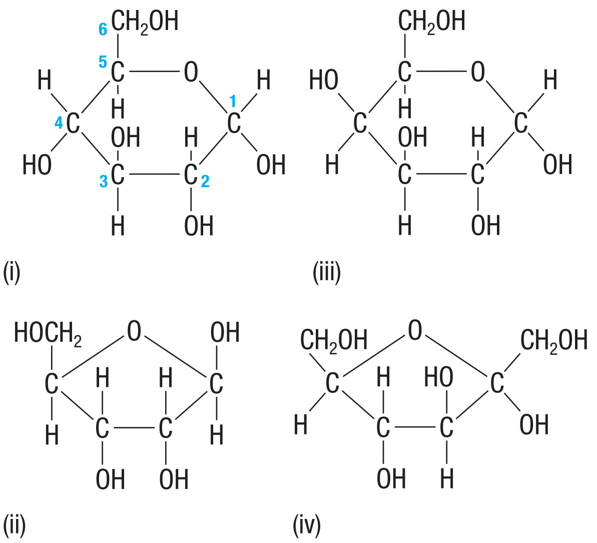
1.4 Review

Summary

- Carbohydrates are simple and complex sugar molecules. They are the most abundant macromolecules found in living things on Earth.
- Monosaccharides are single sugar molecules that have a 1:2:1 ratio of C:H:O. Disaccharides consist of two single sugar subunits that are linked through a dehydration synthesis reaction. Polysaccharides are long chains of sugar monomers.
- Carbohydrates are polar molecules. They are soluble in water, unless they are very large.
- Lipids are generally non-polar molecules that do not readily dissolve in water.
- Fatty acids and triglycerides are primarily energy-storage molecules. Triglycerides consist of three fatty acid chains linked to glycerol.
- Phospholipids are the main component of all plasma membranes. They are formed from a glycerol molecule, two fatty acids, and an ionic phosphate-containing group.
- Steroids are small lipids with a four-carbon ring structure.
- Waxes are long fatty acid chains linked to alcohol or ring structures. They function primarily as waterproofing compounds.

Questions

1. (a) Define the term "isomer."
   (b) Which of the molecules in **Figure 13** are isomers? Explain your reasoning. K/U T/I



(i) (iii)

(ii) (iv)

Figure 13

2. Relate the chemical structure of carbohydrates to their physical properties and uses. K/U
3. Humans use carbohydrates in many ways. Research how humans use monosaccharides, disaccharides, and polysaccharides. T/I
4. Compare the polarity of carbohydrates and lipids. How does their polarity relate to their physical properties? K/U
5. Why are most polysaccharides insoluble in water? K/U
6. (a) Distinguish between a fatty acid and a fat.
   (b) What happens to the acidic properties of a fatty acid when a fat is formed? K/U
7. Why are steroids important, even though they tend to have a bad reputation? T/I
8. Investigate the use of one performance-enhancing drug in the steroid group. What are the medical consequences of its use? How do sports federations check for the presence of steroids? T/I

WEB LINK

Proteins and Nucleic Acids

Spiderwebs, egg white, and even horses' hooves are made of protein. A **protein** is a polymer that has many subunits folded into a three-dimensional structure that specifies its function. The importance of proteins in nature is evident in their name, which comes from the Greek word *proteois*, meaning "first place." Proteins are the most diverse group of molecules in living systems, in terms of their structure and function. They are the real workers of the cell, carrying out vital structural and functional roles.

Nucleic acids are another important type of molecule. They are necessary for protein production in cells. Nucleic acids carry our genetic information, which is passed on from our parents and makes us who we are. Genetic information passes from one type of nucleic acid, DNA, into another type of nucleic acid, RNA. RNA chemical information is then translated for the synthesis of proteins (Chapter 7). The close relationship between DNA, RNA, and proteins keeps our cells functioning properly.

protein a large molecule that consists of many amino acid subunits that are joined together by peptide bonds folded into a specific three-dimensional shape

nucleic acid a blueprint for proteins that are synthesized in cells; stores hereditary information

Amino Acids

All proteins are polymers that are composed of amino acid monomers. An **amino acid** has a central carbon atom attached to an amino group ($-NH_2$), a carboxyl group ($-COOH$), and a hydrogen atom. In solution, the amino group bonds to an H^+, while the carboxyl group releases an H^+ (**Figure 1**). Attached to the central carbon atom is a variable side group, called an R group, which gives each amino acid its distinct characteristics.

amino acid a molecule that contains a carboxyl group and an amino group; serves as the monomer subunit of proteins

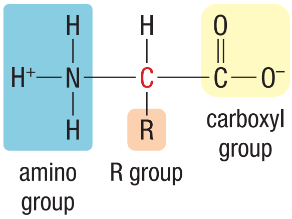


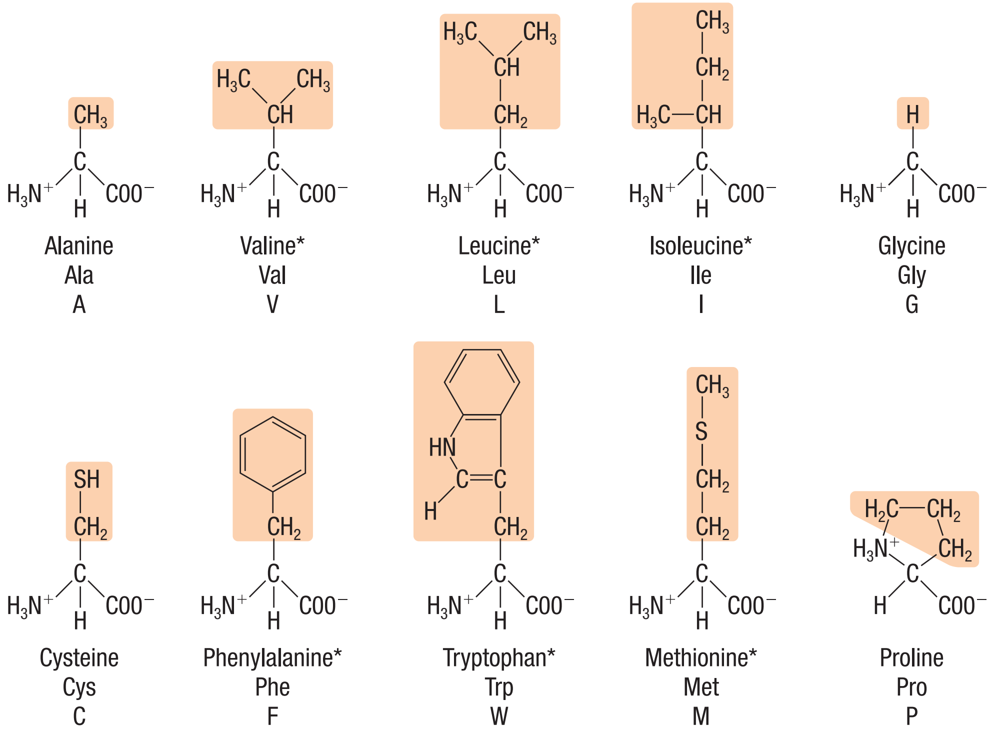
Figure 1 Every amino acid has a central carbon atom with a carboxyl group at one end and an amino group at the other end, as well as a hydrogen atom and an R group.

There are 20 different amino acid side groups, or R groups, ranging from a single hydrogen atom to complex carbon chains or rings (**Figure 2**, next page). The one exception to this organization is the amino acid proline, which has a ring structure that includes the nitrogen and central carbon atoms. Differences in these side groups give the amino acids their individual properties. Side groups may be polar or nonpolar. Among the polar side groups, some carry a positive or negative charge and others act as acids or bases.

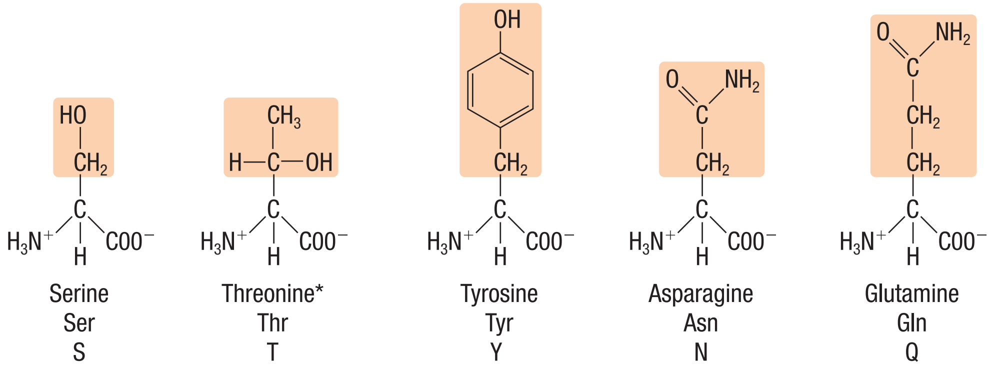
Many of the amino acid side groups contain a reactive functional group, such as $-NH_2$, $-OH$, $-COOH$, or $-SH$, which may interact with atoms located elsewhere in the same protein or with molecules and ions located outside the protein. With few exceptions, all proteins in living things are an assembly of various numbers and combinations of 20 different amino acids. Eight of these amino acids are considered essential for humans because they can only be obtained from our diet. The rest can be synthesized by the cells. There are also other amino acids, which include some neurotransmitters.

Proteins

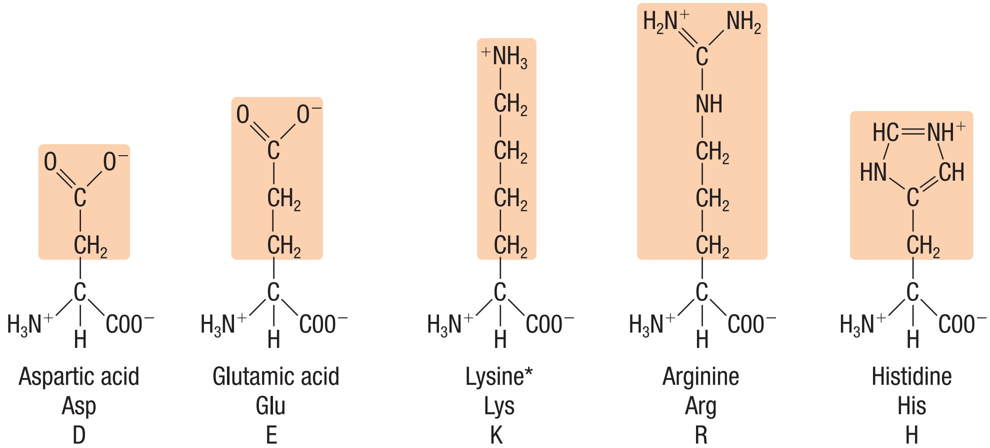
Proteins are by far the most complex molecules in living organisms. There are thousands of different proteins in your body and around you, performing thousands of tasks. The strands of hair on your head, and the tendons and ligaments that connect your muscles and bones, contain structural proteins.



non-polar amino acids



uncharged polar amino acids



negatively charged (acidic) polar amino acids

positively charged (basic) polar amino acids

Figure 2 The structures of all 20 amino acids found in proteins. Every amino acid has the same basic structure, with the exception of proline. Below each amino acid is its name, followed by its three-letter abbreviation and its letter symbol. The asterisk denotes essential amino acids that must be obtained from nutrients.

Structural proteins provide much of the supportive framework of the cells (**Figure 3**). Defensive proteins called antibodies, which are found in the human body, help to fight off infections.

Figure 3 (a) Structural proteins are found in your hair. (b) A vaccine triggers the production of defence proteins. (c) The egg white and yolk inside a bird's egg contain proteins that are essential for the developing embryo. (d) Spider silk is a protein that is used to make a spiderweb.

Hormones and other messenger chemicals in the cell are signal proteins. Hemoglobin is a special protein in red blood cells that delivers oxygen to muscle and other tissues and organs. Transport proteins shuttle substances across biological membranes. Egg whites contain storage proteins to provide essential chemical building blocks for developing embryos. Other proteins serve as recognition and receptor molecules at the surfaces of cells, and some regulate the activity of other proteins and DNA. Motile proteins give cells and cellular structures the ability to move. Perhaps most importantly, special proteins called enzymes are largely responsible for making almost every biochemical reaction possible. They speed up the rate of chemical reactions. **Table 1** summarizes the functions of the various types of proteins.

Table 1 Different Types of Proteins and their Functions

Type of protein	Function	Example
structural	framework support	hair, tendons, and ligaments
defensive	infection fighters	antibodies
signal	messenger	hormones
carrier	transport of materials	hemoglobin
recognition and receptor	cellular markers	major histocompatibility complex
enzyme	catalyst	amylase
motile	movement	actin and myosin

Peptides

Peptide bonds link many amino acids into chains of subunits that make proteins. A peptide bond is a covalent bond that is formed by a dehydration synthesis reaction between the $-NH_2$ group of one amino acid and the $-COOH$ group of a second amino acid (**Figure 4**, next page). An amino acid chain always has an $-NH_2$ group at one end, called the N-terminal end, and a $-COOH$ group at the other end, called the C-terminal end. In cells, amino acids are added only to the $-COOH$ end of the growing peptide strand. The chain or polymer of amino acids that is formed by sequential peptide bonds is called a **peptide**. Unlike carbohydrate chains, there are no side branches of amino acids in a peptide, although many functioning proteins contain small non-amino acid components. A **polypeptide** is a peptide that is greater than 50 amino acids in length. A protein is one or more polypeptides that are folded into a precise three-dimensional shape. Only after folding occurs is the protein able to function.

peptide bond a covalent bond that links amino acids

peptide a chain of amino acid subunits that are connected by peptide bonds

polypeptide a peptide with more than 50 amino acids

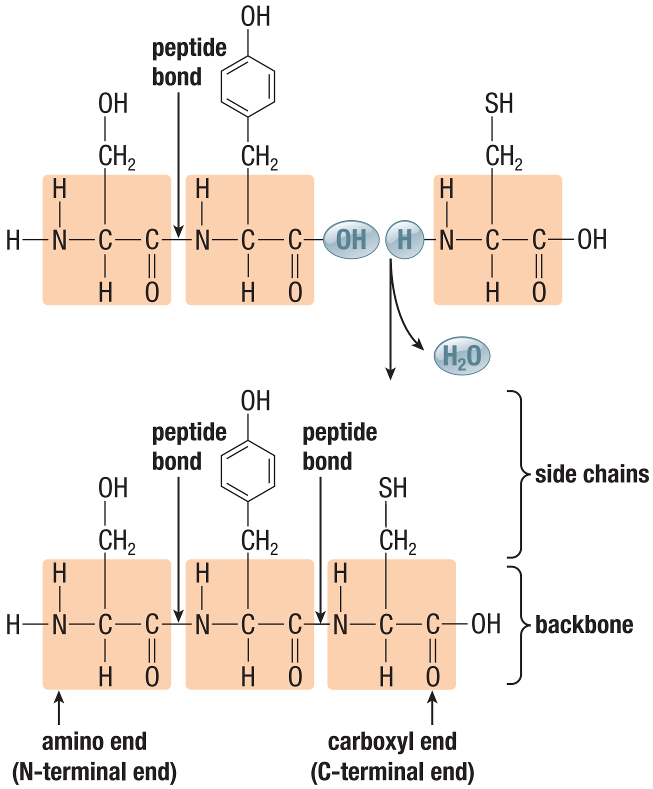


Figure 4 A peptide bond forms between two amino acids in a growing chain through a dehydration synthesis reaction. A water molecule is released as the bond forms between the carboxyl group of one amino acid and the amino group of another. The growing amino acid chain always has an amino group at one end and a carboxyl group at the other end.

Protein Structure

Proteins have up to four levels of structure, with each level imparting different characteristics and degrees of complexity to the overall protein.

PRIMARY STRUCTURE

The primary structure of a protein is the unique linear sequence of its amino acids in each polypeptide chain (**Figure 5(a)**, next page). Changing even a single amino acid in the primary structure will alter the overall structure of the protein to some degree. A single change can alter or even destroy the biological function of the protein.

There is an enormous diversity in the primary structures that can form. With 20 possible amino acids, there are 20^2, or 400, different combinations possible by joining only two amino acids. Furthermore, there are 20^3, or 8000, combinations possible by joining only three amino acids. The possible combinations of lengthy primary structures are virtually limitless.

SECONDARY STRUCTURE

Most polypeptides have portions that repeatedly coil or fold into patterns and contribute to the overall shape of a protein. This secondary structure is the result of hydrogen bonding between different parts of the same amino acid backbone. Specifically, hydrogen bonding occurs between electronegative nitrogen and oxygen atoms and partially positive hydrogen atoms.

Two common secondary structures are the beta-pleated (or β-pleated) sheet and the alpha-helix (or α-helix) (**Figure 5(b)**, next page). A β-pleated sheet forms by a side-by-side alignment of the amino acid chain. β-pleated sheets play an important role in the strength of silk. An α-helix is a delicate coil that is held together by hydrogen bonds between every fourth amino acid. It is found in filamentous proteins and transmembrane proteins, and it provides the necessary structure for their functions.

TERTIARY STRUCTURE

The secondary structure of a protein is the result of interactions between atoms in the backbone. The tertiary structure of a protein is the overall three-dimensional shape of a protein due to a range of bonding interactions among the amino acid R groups (**Figure 5(c)**). Recall, from Figure 2 (page 40), the different types of R groups. It is in the tertiary structure that the intermolecular reactions of the R groups determine the three-dimensional shape of the polypeptide chain. These intermolecular reactions include ionic bonds, hydrogen bonds, hydrophobic interactions, and disulfide bridges (**Figure 5(d)**). Hydrophobic interactions are the interaction of non-polar side groups that cluster together as a result of other amino acid R groups interacting with water. A disulfide bridge is the bond that is formed when the —SH groups of two cysteine amino acids line up and react to form an S—S covalent bond. This is a strong bond that holds two parts of the polypeptide strand together, stabilizing its shape. The tertiary structure is critical to the functions of proteins, especially enzymes. Extreme conditions (such as temperature and pH) can unfold a protein, causing **denaturation**, a loss of both the structure and the function of the protein.

denaturation the loss of both the structure and function of a protein

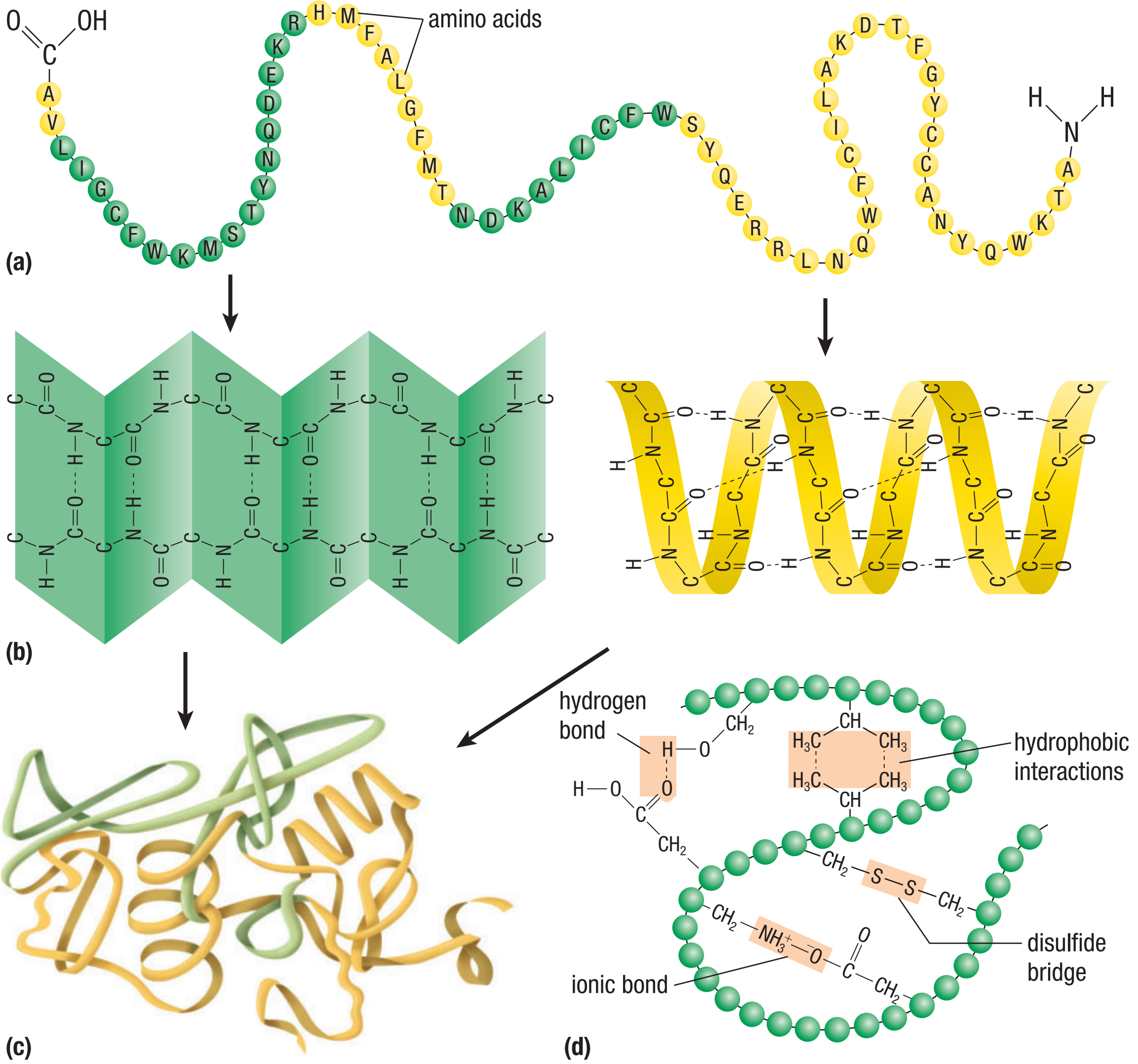


Figure 5 (a) The primary structure of a protein is the sequence of amino acids in a polypeptide strand. Each bead on the strand represents an individual amino acid. (b) Portions of the amino acid chain can fold and spiral. This secondary structure is frequently a folded β-pleated sheet (left) or a spiral α-helix (right). (c) (d) The polypeptide further folds into its tertiary structure, which is dependent on the amino acid side chains.

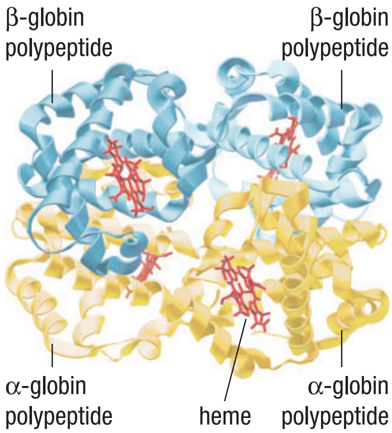


Figure 6 Hemoglobin is the combination of four polypeptides. The heme ring of each polypeptide is shown in red.

QUATERNARY STRUCTURE

Many proteins are composed of two or more polypeptides that come together to form the final functional proteins. This quaternary structure, which forms subunits, exists in many proteins. The same bonds and forces that fold single polypeptide chains into tertiary structures (including hydrogen bonds, polar and non-polar attractions, and disulfide linkages) also hold the multiple polypeptide chains together. The hemoglobin molecule is composed of four polypeptides, each consisting of more than 140 amino acids (**Figure 6**).

PROTEIN PROSTHETIC GROUPS

Besides properly folded polypeptide chains, many proteins require non-protein components, called prosthetic groups, to function. One example is found in hemoglobin, the major protein that is involved in O_2 transport in vertebrates. In hemoglobin, the four polypeptides do not bind the oxygen. Rather, the oxygen is bound to heme groups, which are themselves surrounded and held by the polypeptides. Each polypeptide chain contains one heme ring, in which there is a single iron (Fe^{2+}) ion (Figure 6). Therefore, there are four heme groups per hemoglobin, and four O_2 are carried. Many enzymes require prosthetic groups that contain metal ions in order to function. For example, some enzymes that are involved the process of cellular respiration require Mg^{2+} ions.

Protein Structure and Functional Relationship

The shape of a protein influences and enables its function. For example, long linear proteins align to form the strong fibres of silk, collagen, and keratin. This long linear formation provides the strength. Compact globular proteins, such as the hemoglobin protein, are good for transport. Hemoglobin proteins transport oxygen to muscles, and their shape enables them to be carried efficiently within red blood cells and through the body. Hemoglobin illustrates the complexity and enormous size of many proteins. A single hemoglobin protein is comprised of thousands of individual atoms, yet its function is to carry just four O_2 molecules. Enzymes and antibodies have special pockets that bind specific molecules, allowing these proteins to carry out their function.

UNIT TASK **BOOKMARK**

Consider how you can apply an understanding of the form and function of proteins as you work on your Unit Task (p. 108).

Mini **Investigation**

Building and Exploring Models of Proteins

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1**

In this activity, you will build and observe three-dimensional models of several amino acids to explore how they assemble into polypeptides.

Equipment and Materials: chemical modelling kit

1. Construct models of a polar amino acid, a non-polar amino acid, and an ionic amino acid of your choice. Use Figure 2 as reference. Choose amino acids with relatively small R groups.
2. Draw each molecule in your lab notebook, and record the overall chemical formula for each amino acid.
3. Form a tripeptide by performing two dehydration synthesis reactions.

A. What gives each amino acid R group its key characteristics to make it polar, non-polar, or ionic? T/I

B. What functional groups are involved in the dehydration synthesis reaction? K/U

C. Explain why the acidic property of the amino acid changes as a result of the dehydration synthesis reaction. T/I

D. Compare the chemical formulas for the amino acids you formed. In what ways are they similar? In what ways are they different? K/U T/I

E. What element that is present in all amino acids is not present in most carbohydrates and lipids? Compare the C:H:O ratio in amino acids with the C:H:O ratios in carbohydrates and lipids. K/U

F. How might the solubility of peptides be influenced by the size of the peptides? How might it be influenced by the R group of the amino acids? T/I

G. Calculate the total number of peptides with 10 amino acids that can be formed from the 20 different types of amino acids. T/I

H. Would you consider the formation of a peptide bond to be an example of a neutralization reaction? Explain your reasoning. T/I

Nucleic Acids

Nucleic acids serve as the assembly instructions for all proteins in living organisms. Two types of nucleic acids exist: DNA and RNA. Deoxyribonucleic acid (DNA) stores the hereditary information that is responsible for inherited traits in all eukaryotes and prokaryotes and in many viruses. Ribonucleic acid (RNA) is the hereditary molecule of some viruses. There are several different forms of RNA involved in protein synthesis in all cells.

Investigation 1.5.1

Testing for Macromolecules (p. 58)
Now that you have learned about macromolecules, you will conduct tests on sample compounds to determine whether they are carbohydrates, lipids, or proteins.

Nucleotides

All nucleic acids are polymers of units called nucleotides. A **nucleotide** consists of three parts linked together by covalent bonds: a nitrogenous base formed from rings of carbon and nitrogen atoms, a 5-carbon ring-shaped sugar, and one to three phosphate groups. In a nucleotide, each nitrogenous base links covalently to a 5-carbon sugar, either deoxyribose or ribose (**Figure 7**). The two sugars differ only in the chemical group that is bound to the 2′-carbon: deoxyribose has an —H, and ribose has an —OH group.

nucleotide the building block of nucleic acids; consists of a 5-carbon sugar, a nitrogenous base, and one to three phosphate groups

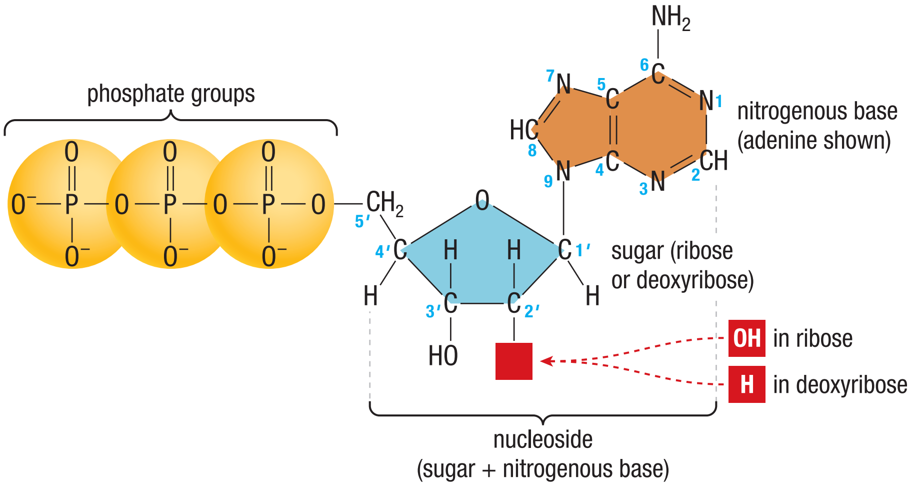

phosphate groups
nitrogenous base (adenine shown)
sugar (ribose or deoxyribose)
OH in ribose
H in deoxyribose
nucleoside (sugar + nitrogenous base)

Figure 7 The chemical structure of a nucleotide. The carbons and nitrogens on the base ring structure are labelled 1 to 9, and the carbons on the sugar are labelled 1′ to 5′. A ribose sugar found in RNA has an —OH bound to the 2′ carbon. The deoxyribose found in DNA has an —H bound to the 2′ carbon.

There are two general types of nitrogenous base: pyrimidines and purines (**Figure 8**). Pyrimidine bases are single organic rings, whereas purine bases are two-ringed organic structures. Both types of bases have a high nitrogen content. The three pyrimidine bases are uracil (U), thymine (T), and cytosine (C). The two purine bases are adenine (A) and guanine (G).

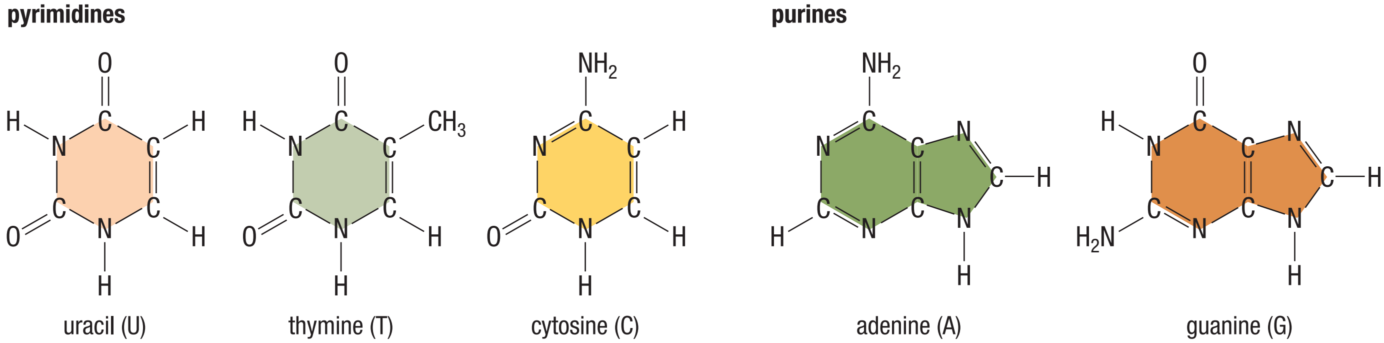


Figure 8 Nucleotide base chemical structures

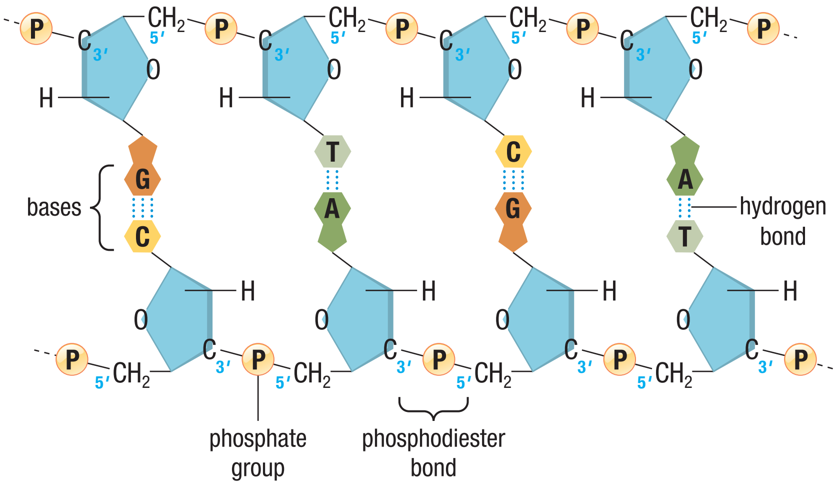
DNA and RNA: Nucleotide Polymers

DNA and RNA consist of chains of nucleotides, called polynucleotide chains, with one nucleotide linked to the next by a single bridging phosphate group between the 5′-carbon of one sugar and the 3′-carbon of the next sugar in line. This type of linkage is called a **phosphodiester bond**. The arrangement of the alternating sugar and phosphate groups forms the backbone of a nucleic acid chain. The nitrogenous bases of the nucleotides

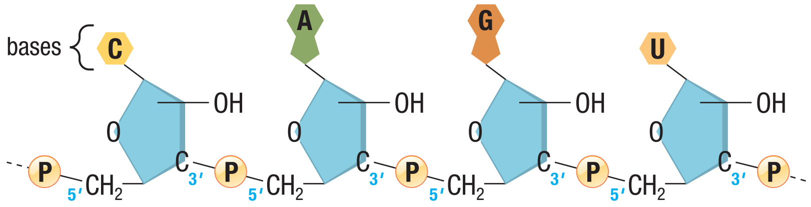
phosphodiester bond a link that is formed between nucleotides by a phosphate bridge project from this backbone. In a DNA chain, each nucleotide contains deoxyribose, a phosphate group, and one of the four bases A, T, G, or C. In an RNA chain, each nucleotide contains ribose, a phosphate, and one of the four bases A, U, G, or C.

antiparallel oriented in opposite directions

DNA is a double-stranded molecule in which the two strands of DNA run **antiparallel** to each other. This means that they are oriented in the opposite direction relative to the sugar-phosphate backbone. The end with the phosphate group is referred to as the 5′ end, and the opposite end of the same strand, with the deoxyribose sugar, is referred to as the 3′ end. Bases on opposite strands of DNA hydrogen bond to one another to form a double-stranded DNA molecule (**Figure 9**). G (guanine) forms three hydrogen bonds with C (cytosine), and A (adenine) forms two hydrogen bonds with T (thymine). As base pairs form between two strands of DNA, the molecule is twisted into a double helix configuration. Although DNA is almost always found as a very long double helix, RNA takes on a greater variety of structures. RNA structures include relatively short linear forms, as well as structures that fold back on themselves in clover or hairpin formations.



(a) DNA



(b) RNA

Figure 9 (a) DNA structure, with the hydrogen bonds between the bases shown with dotted lines; (b) RNA structure

Nucleotides perform many functions in cells, in addition to serving as the building blocks of nucleic acids. Two nucleotides in particular, adenosine triphosphate (ATP) and guanosine triphosphate (GTP), are the primary molecules that transport chemical energy from one reaction system to another (Chapter 3). These nucleotides also regulate and adjust cellular activity.

Carbohydrates, Lipids, Proteins, and Nucleic Acids

There are four major types of biological molecules: carbohydrates, lipids, proteins, and nucleic acids. Each type of molecule has many different roles in cellular processes. Throughout this course, you will learn more about these cellular processes and the roles of the four types of molecules as they work together in various combinations. For example, you will learn how carbohydrates and lipids are used to store, transfer, and release energy as you study cellular metabolism. You will learn how inherited chemical information is stored in nucleic acids, translated into proteins, and acted upon through a variety of molecules as you study genetics. You will also learn how chemical processes sustain a dynamic equilibrium within each cell and within each organism as a whole.

Investigation 1.5.2

Manipulating Macromolecules (p. 60)
Computer-generated molecules can be used as a tool to study the structure and function of large molecules. In this investigation, you will explore computer-generated macromolecules.

1.5 Review

Summary

- Amino acids are the monomer building blocks of proteins. There are 20 different amino acids. They all contain an amino group, a carboxyl group, and an R group. The R group gives each amino acid its unique characteristics.
- Proteins are complex polymers. They have primary, secondary, tertiary, and quaternary levels of structure, which contribute to their functions.
- Some proteins require non-protein components, called prosthetic groups, to function properly.
- All nucleotides consist of three parts: a nitrogenous base, a 5-carbon sugar, and one to three phosphates.
- DNA and RNA are polymers of nucleotides.
- The two general types of nitrogenous bases are pyrimidines (uracil, thymine, and cytosine) and purines (adenine and guanine).

Questions

1. What groups of atoms are found in all amino acids? K/U
2. Describe the difference between the primary and secondary protein structures. K/U
3. Explain why it is necessary for a protein to adopt specific tertiary and quaternary arrangements. K/U
4. Explain the role of hydrogen bonding and disulfide bonds between R groups. K/U
5. List some of the different types of proteins and their functions. Identify specific applications of these proteins in various living organisms. K/U
6. Relate the diversity in protein structure to the diversity in protein function. T/I
7. A researcher studying a newly discovered small protein finds that when dissolved in water, the solution has a pH above 7. T/I
   (a) What amino acids would you predict to be abundant in this protein? Why?
   (b) What amino acids would you predict to be uncommon in this protein? Why?
8. What is the role of the sugar and phosphate groups in the structure of nucleic acids? K/U
9. Explain the similarities and differences between DNA and RNA. K/U T/I
10. Draw the linkage of two nucleotides and two amino acids. T/I
11. How does the function of nucleic acids differ from that of other types of macromolecules? K/U
12. Your biology teacher tells you that nucleic acids, fatty acids, and amino acids can increase the H^+ concentration of a solution. Explain how this is possible. T/I
13. The human body can synthesize 12 of the 20 amino acids. Eight amino acids, called essential amino acids, must be obtained from the food we eat. Select one of these essential amino acids (see Figure 2, page 40). Research your selected amino acid and answer the following questions. T/I
    (a) Describe your amino acid's function in the human body.
    (b) What sources of food contain this amino acid?
    (c) What symptoms will a person experience if they are deficient in this amino acid?
14. Oxytocin and vasopressin are hormones with very different functions but relatively similar structures. Using the Internet and other sources, find the answers to the following questions. T/I
    (a) What are the general functions of each hormone?
    (b) They are both nine-amino-acid polypeptides but have two amino acids that are different. Which two amino acids in these hormones are different?

WEB LINK

1.6 *Biology* JOURNAL

Linus Pauling: Creativity and Controversy in Science and Society

SKILLS HANDBOOK A3

ABSTRACT

Driven by his desire to understand our world, Linus Pauling made important discoveries in chemistry, physics, and biology. He investigated atomic structures and chemical bonding, and he made important discoveries related to genetic diseases, immunology, nutritional therapy, and biomedicine. He wrote a series of papers about chemical bonding, which eventually led to a Nobel Prize in Chemistry in 1954. Pauling was also an activist who protested the development, testing, and use of nuclear weapons. His efforts earned him the Nobel Peace Prize in 1962. He is the only person, to date, to have ever received two unshared Nobel prizes.

Contributions to Science: The Structure of Proteins

Linus Pauling (1901–1994) began his career as a scientist in the fields of chemistry and physics (**Figure 1**). His early research focused on the formation of chemical bonds between atoms in molecules and crystals. Using quantum mechanics, X-ray diffraction, and, later, electron diffraction, Pauling formulated generalizations about atomic arrangements in crystals that are held together by ionic bonds. What came to be known as "Pauling's Rules" still remain a useful guide for understanding crystal structures.

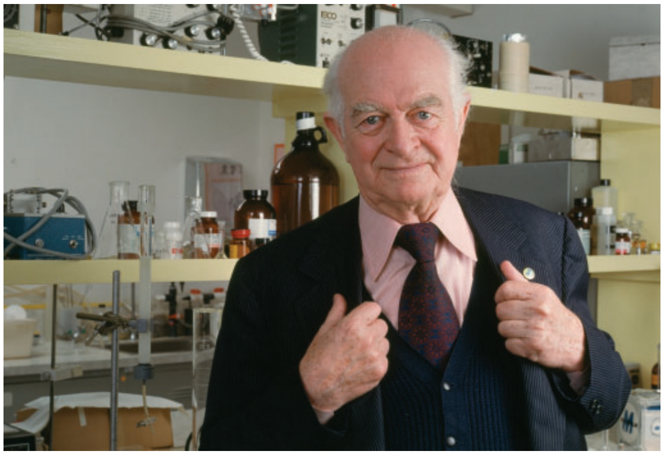


Figure 1 Linus Pauling (1901–1994)

Pauling also established the electronegativity scale of elements. He noted that the smaller the difference in electronegativity between two atoms, the more the bonding approached a pure covalent bond. In other words, when atoms have an equal electronegativity value, they share the electrons equally, creating a true covalent bond. Pauling developed two major new concepts to explain this concept of covalent bonding, or the sharing of electrons between two atoms. These concepts allowed him to determine that the optimal bonding pattern of a carbon atom creates bonds directed toward the four corners of a tetrahedron. Since carbon is the central atom of organic molecules, this theory attracted the attention of many scientists worldwide.

By 1948, Pauling and his colleagues had gathered considerable evidence about the bonding angles and distances between the atoms in amino acids, as well as insight into the fundamental structure of proteins. This insight led Pauling to describe the two fundamental secondary structures of proteins: the α-helix and the β-pleated sheet (**Figure 2**).

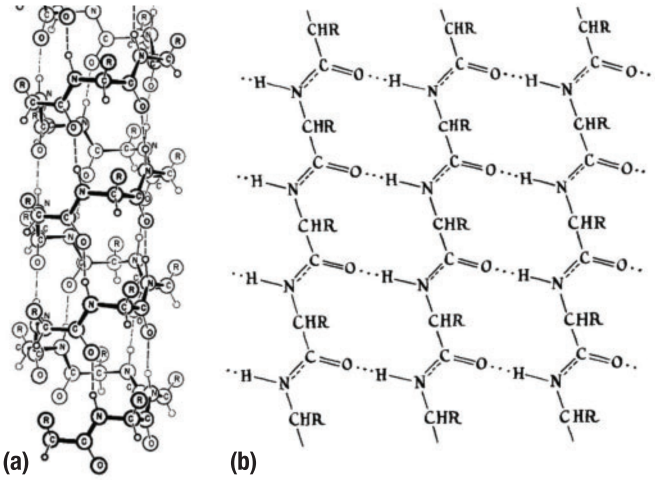


Figure 2 Pauling's representation of (a) an α-helix protein structure with 3.7 amino acid residues per turn, and (b) a hydrogen bonded β-pleated sheet, from his original papers published in 1951

Pauling based his theoretical configurations on principles of chemical bonding and X-ray diffraction data. Subsequent X-ray diffraction studies have proven that the α-helix and β-pleated sheets are major components of protein structure. One or both occur in almost all proteins.

In an interview in which he reflected on his discovery of protein secondary structures, Pauling commented that he began his work on determining three-dimensional protein structures in 1937, and it was not until 11 years later that he actually determined those structures.

Pauling and his colleagues wrote nine papers, including seven published back to back in the same year in the journal *Proceedings of the National Academy of Sciences*. These now-famous articles, known as the "Protein Papers," established the first fundamental understanding of the structures of proteins and laid much of the foundation for modern molecular biology. For his great scientific achievements, Pauling was awarded the 1954 Nobel Prize in Chemistry.

Contributions to Society: Challenging Authority

Linus Pauling's efforts were not limited to science. He became a leading advocate against nuclear arms. In the 1950s, Pauling spoke out against the atmospheric testing of nuclear weapons and the buildup of arsenals. As a result, the U.S. government branded him a "communist sympathizer" and viewed him as a threat, which lead to his passport being revoked in 1952. This action may have prevented him from contributing more to the understanding of DNA structure, since he was unable to travel overseas to pursue his research.

In 1958, he started a petition to end nuclear testing and obtained the signatures of 11 000 scientists worldwide. He presented scientific data and statistics to argue that radioactive fallout causes an increase in incidences of cancer, genetic disorders, and birth defects. He also published the book *No More War!* in 1958. For all his efforts, he was awarded the 1962 Nobel Peace Prize. Instead of attending a party at the White House honouring Nobel laureates, he spent the day outside the gates carrying a sign protesting nuclear testing.

A Fulfilling Life

Linus Pauling was a multi-faceted genius who remained active in science and society well into his 80s. When he died at age 93 in 1994, the world lost one of its greatest scientists and humanitarians. In his lifetime, Linus Pauling published over 1000 articles and books. His landmark book, *The Nature of the Chemical Bond*, is cited as the most influential science book of the twentieth century. Pauling was a scientist who took many professional and personal risks. He expressed ideas that were interpreted as unorthodox but led to some of the most significant theories and discoveries in science. He also maintained a strong moral position and roused the public to take action for worthy causes.

After retiring in 1973, Pauling cofounded a non-profit biomedical research organization, now called the Linus Pauling Institute. Pauling became a prominent advocate for the use of nutrients to achieve a healthy, prolonged life. Despite all of his significant achievements, Pauling may be best known for his controversial stance on the benefits of megadoses of vitamins. He promoted the consumption of very high doses of certain vitamins, especially vitamin C, as a non-toxic alternative to medicines such as chemotherapy for cancer patients. Faced with many critics, Pauling adamantly maintained his position and refused to accept results that refuted his claims about the benefits of high doses of vitamins. This claim has never been verified by other scientists. In fact, numerous independent studies by researchers at the Mayo Clinic and elsewhere have shown that high doses of vitamin C have no health benefits for cancer patients.

Further Reading

Goertzel, T., & Goertzel, B. (1995). *Linus Pauling: A life in science and politics*. New York, NY: Basic Books.

Pauling, L. (1995). *Linus Pauling in his own words: Selections from writings, speeches, and interviews* (B. Marianacci, Ed.). New York, NY: Simon & Schuster.

National Library of Medicine. *Profiles in science: The Linus Pauling papers*. Retrieved June 1, 2011. 🌐

🌐 WEB LINK

1.6 Questions

1. For what accomplishments was Linus Pauling awarded a Nobel Prize? K/U
2. What significant contributions did Linus Pauling make to the field of biology? K/U
3. What did Linus Pauling state as biological reasons to stop the atmospheric testing of nuclear weapons? K/U
4. How did Pauling's personal views on the military and government activities affect his reputation as a person and as a scientist? How did this affect his ability to conduct research? T/I
5. What examples in this article underline the challenges that scientists face when attempting to make significant discoveries in science? K/U T/I
6. Go online, and read some of the personal letters between Pauling and his friends and colleagues. Report back on the contents of these letters. What insights do they offer about Pauling as an individual and as a scientist? 🌐 T/I C

🌐 WEB LINK

1.7 Enzymes

enzyme a biological catalyst, usually a protein, that speeds up a chemical reaction

The cellular activity of all living organisms is controlled through the use of enzymes. An **enzyme** is a special type of biological molecule that usually speeds up a chemical reaction without being consumed or changing the products of the reaction. Almost all enzymes are proteins. There are about 4000 different enzymes in a typical living cell. If even one of these enzymes is missing or defective, the results can be disastrous. The enzyme lipase speeds up the hydrolysis of the lipid triglycerides. Sucrase speeds up the hydrolysis of sucrose into glucose and fructose. These are important reactions that a cell may require for energy and survival.

substrate a substance that is recognized by and binds to an enzyme

Another term that is used to describe an enzyme is "catalyst." A catalyst is a substance that speeds up a reaction without being consumed by the reaction. In biological systems, specific enzymes catalyze particular cellular reactions. Each enzyme has a unique three-dimensional shape, and this shape determines which reaction it catalyzes. For a chemical reaction to move forward, it must overcome an energy barrier, and this is where enzymes are important. Enzymes bind a specific reactant (or reactants), called a **substrate**; in doing so, they lower the energy barrier so that the reaction proceeds at a faster rate than it would without the enzymes (Section 3.3).

Enzymes and Substrates

In a reaction that uses an enzyme, the enzyme combines briefly with the substrate(s) and, after releasing the products, is unchanged. For example, hydrogen peroxide is a toxic chemical that occurs in cells as a by-product of metabolism. To prevent cell damage, hydrogen peroxide is broken down by the enzyme catalase:

$$2\ H_2O_2 \xrightarrow{\text{(catalase)}} 2\ H_2O + O_2$$

active site a pocket or groove in an enzyme that binds its substrate

Each type of enzyme catalyzes the reaction of only one type of molecule or one group of closely related molecules. Enzyme specificity explains why a typical cell needs about 4000 different enzymes to function properly. Enzymes are much larger than the substrate. The substrate interacts with only a very small region of the enzyme called the active site. The **active site** is usually a pocket or groove that forms when the newly synthesized enzyme folds into its correct three-dimensional shape (tertiary structure).

In the early twentieth century, biochemists proposed the lock-and-key hypothesis to explain how specific enzymes and substrates interact. The analogy worked well to explain how even similar substrates (the "keys") were unable to bind to the same enzyme (the "lock") and undergo catalysis. However, the more recent introduction of the induced-fit hypothesis better explains the enzyme-substrate relationship.

Induced-Fit Hypothesis

induced-fit model a model of enzyme activity that describes how an enzyme changes shape to better accommodate a substrate

Research by enzymologists shows that enzymes are not rigid objects, like locks, but are flexible. Just prior to substrate binding, the enzyme changes its shape, or what is called its conformation, so that the active site becomes even more precise in its ability to bind to its substrate (**Figure 1**). This is called the **induced-fit model**.

CAREER LINK

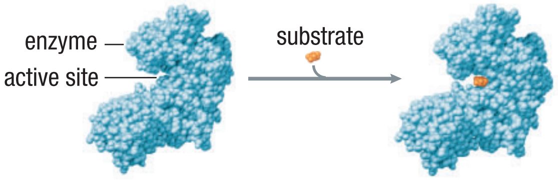


Figure 1 This space-filling model shows the combination of an enzyme, hexokinase (blue), with its substrate glucose (orange). Note that the enzyme undergoes a conformational change, closing the active site more tightly as it binds the substrate.

An enzyme binds to one or more substrates, forming an enzyme-substrate complex. The enzyme then converts the substrate(s) into one or more products. Since enzymes remain unchanged after a reaction, enzyme molecules can rapidly bind to other substrate molecules, catalyzing the same reaction repeatedly. This is the enzyme cycle (**Figure 2**). The rate at which enzymes catalyze reactions varies depending on the enzyme and substrates involved, but typical rates vary between about 100 and 10 million substrate molecules per second!

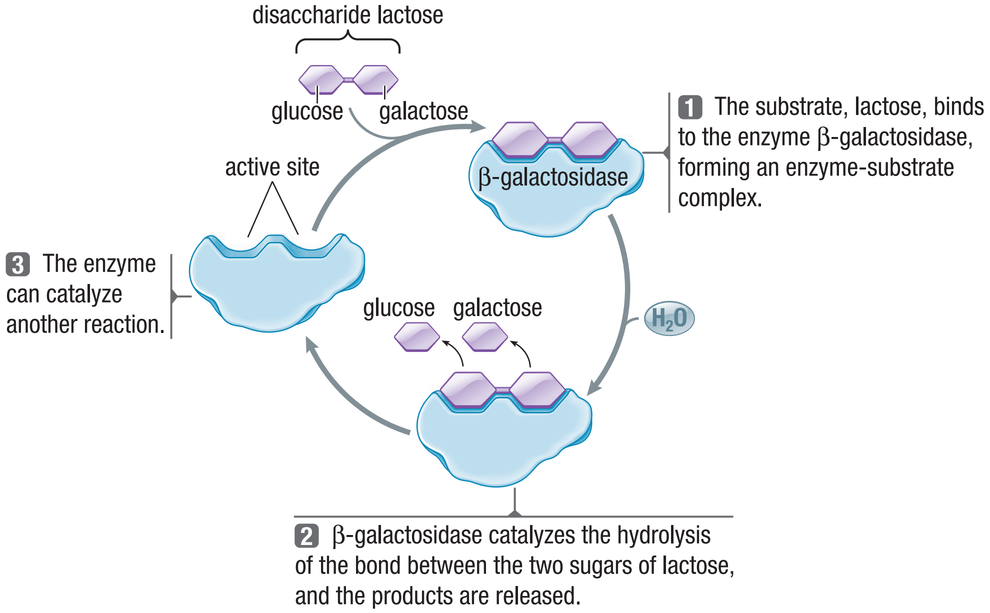

disaccharide lactose
glucose
galactose
active site
β-galactosidase
1 The substrate, lactose, binds to the enzyme β-galactosidase, forming an enzyme-substrate complex.
3 The enzyme can catalyze another reaction.
glucose
galactose
H_2O
2 β-galactosidase catalyzes the hydrolysis of the bond between the two sugars of lactose, and the products are released.

Figure 2 In the catalytic cycle shown, the enzyme β-galactosidase hydrolyzes lactose (a sugar) to produce glucose and galactose. The enzyme is recycled after the reaction is catalyzed. Note that water is a reactant in this reaction.

Mini **Investigation**

Modelling Enzymes and Polymers

Skills: Performing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1**

In this activity, you will model the interaction of an enzyme and its two substrates.

Equipment and Materials: coloured paper clips; strip of paper, approximately 5 cm × 22 cm

1. Prepare a strip of paper as shown in **Figure 3(a)**.
2. Fold the paper as shown in **Figure 3(b)**.
3. Place paper clip substrate 1 on active site 1, spanning the back two layers of the paper enzyme. Place paper clip substrate 2 on active site 2, spanning two layers of the paper enzyme (**Figure 3(c)**).
4. Briskly pull the two tabs apart to “activate” the enzyme (**Figure 3(d)**).
5. Try to produce a “triclipide” or a “tetraclipide” with one pull of the tabs.

A. Explain how the action of the paper enzyme partly models a real enzyme-catalyzed condensation reaction. T/I

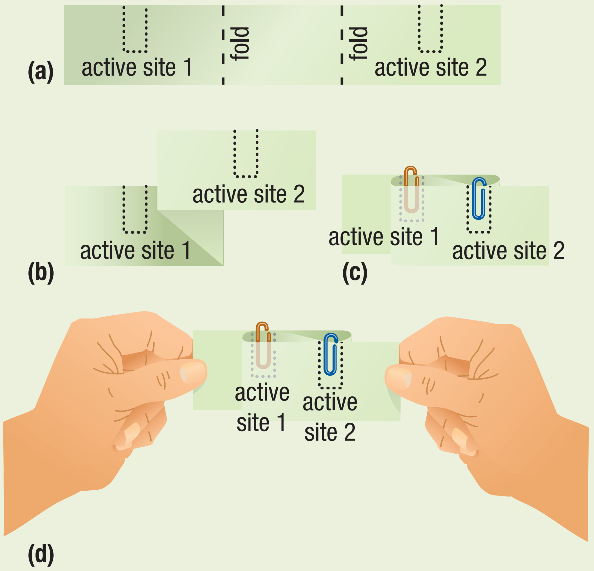


Figure 3

Cofactors and Coenzymes

cofactor a non-protein group that binds to an enzyme and is essential for catalytic activity

Many enzymes require a **cofactor**, which is a non-protein group that binds very precisely to an enzyme. Cofactors are often metals, such as iron, copper, zinc, and manganese. Although your body may need only very small amounts of some of these metals, they are absolutely essential for the catalytic activity of the enzyme to which they bind. For example, an enzyme that is essential for providing one of the key components of the chemical pathway within mitochondria for the production of energy requires a magnesium cofactor to function properly.

coenzyme an organic molecule that acts as a cofactor of an enzyme

Organic cofactors called **coenzymes** play similar roles and are often derived from water-soluble vitamins. Many coenzymes shuttle molecules from one enzyme to another. One of the most important coenzymes is nicotinamide adenine dinucleotide (NAD^+), a derivative of vitamin B_3 (niacin). NAD^+ acts as an electron carrier during a number of biochemical pathways.

Conditions and Factors That Affect Enzyme Activity

Several conditions can alter enzyme activity, including enzyme and substrate concentration, temperature, and pH. In addition, several control mechanisms modify enzyme activity. These control mechanisms adjust reaction rates to meet a cell's requirements for chemical products.

Enzyme and Substrate Concentration

The concentration of both the enzyme and the substrate will influence the rate of a catalysis reaction. If there is excess substrate present, then the rate of reaction is proportional to the enzyme concentration (**Figure 4(a)**). This occurs because the amount of enzyme limits the rate of reaction. If, however, the amount of enzyme is at a constant intermediate concentration, then increasing the substrate concentration will increase the rate of reaction up to a point, called the saturation level (**Figure 4(b)**). The rate of the reaction increases as collisions become more frequent. However, as the enzyme molecules approach the maximum rate at which they combine with the substrate, increasing the substrate concentration has a reduced effect. Eventually, the rate of reaction levels off. At this point, the enzyme molecules are saturated with substrate.

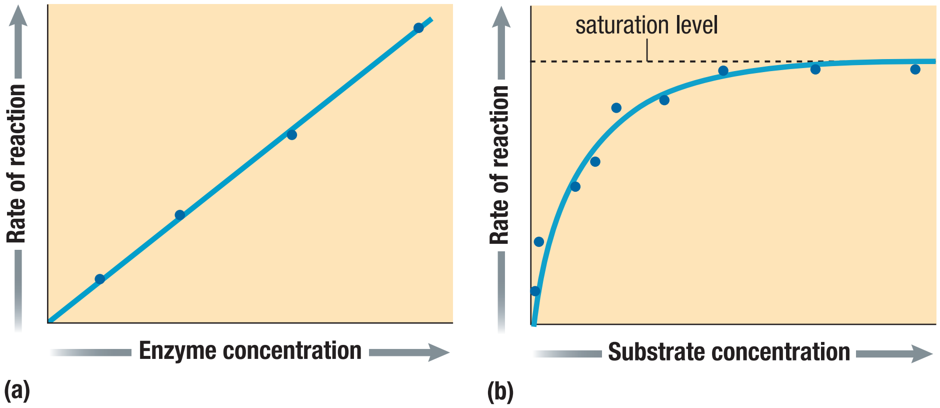


Figure 4 (a) The rate of a reaction (usually measured as the rate of product formation) is proportional to the enzyme concentration if the concentration of the substrate is constant and at a high level.
(b) The rate of a reaction as a function of increasing substrate concentration is a curve if the amount of enzyme is kept constant.

Enzyme Inhibitors

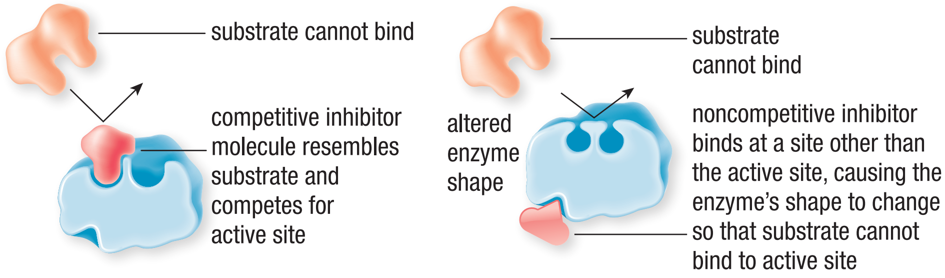
Enzyme inhibitors lower the rate at which an enzyme catalyzes a reaction. Inhibitors are molecules that bind to an enzyme and decrease its activity. Some inhibitors work by binding to the active site of an enzyme, while other inhibitors bind to critical sites located elsewhere in the structure of the enzyme.

Inhibitors that combine with the active site have shapes that resemble the normal substrate closely enough to fit into and occupy the active site. When binding to the active site, inhibitors block access to the normal substrate and slow the rate of the reaction. If the concentration of the inhibitor is high enough, the reaction stops completely. This type of inhibition is called **competitive inhibition** because the inhibitor actually competes with the normal substrate for access to the active site of the enzyme (**Figure 5(a)**).

In **noncompetitive inhibition**, specific molecules inhibit enzyme activity, but they do not compete with substrate molecules for binding to the active site (**Figure 5(b)**). Instead, noncompetitive inhibitors bind to an enzyme at a location other than the active site. This changes the shape of the enzyme, reducing the ability of the substrate to bind efficiently.

competitive inhibition a situation in which a competitor substance binds to a normal substrate binding site to block enzyme activity

noncompetitive inhibition a situation in which molecules bind to an enzyme at a site that is not the active site, thus blocking enzyme activity


substrate cannot bind
competitive inhibitor molecule resembles substrate and competes for active site
substrate cannot bind
altered enzyme shape
noncompetitive inhibitor binds at a site other than the active site, causing the enzyme's shape to change so that substrate cannot bind to active site

(a) competitive inhibition

(b) noncompetitive inhibition

Figure 5 Actions of enzyme inhibitors: (a) competitive inhibition and (b) noncompetitive inhibition

Inhibitors differ in how strongly they bind to enzymes. In reversible inhibition, the binding of the inhibitor to the enzyme is weak and readily reversible. Enzyme activity returns to normal following the release of the inhibitor. By contrast, some inhibitors bind so strongly to the enzyme through the formation of covalent bonds that they completely disable the enzyme. This is irreversible inhibition.

Not surprisingly, many irreversible inhibitors that act on critical enzymes are highly toxic to the cell. Irreversible inhibitors include a wide variety of drugs and pesticides. Cyanide is a potent poison because it binds strongly to and inhibits cytochrome oxidase, the enzyme that catalyzes a key step in cellular respiration. Many antibiotics are toxic to bacteria and work by inhibiting enzyme activity in the bacteria. Irreversible inhibition can be overcome only by the cell synthesizing more of the enzyme. The antibiotic penicillin acts by inhibiting the synthesis of peptidoglycan, a key component of the bacterial cell wall. The enzyme transpeptidase catalyzes the formation of a peptide bond between the two amino acids that are responsible for linking two parts of peptidoglycan. The structure of penicillin mimics the structure of the two amino acids that are normally brought together by the active site. Penicillin binds irreversibly to the active site of transpeptidase, effectively destroying the molecule.

ALLOSTERIC CONTROL OF ENZYME ACTIVITY

Molecules that naturally regulate enzyme activity in a cell often behave somewhat like a noncompetitive reversible inhibitor. These regulatory molecules bind to an enzyme on a site that is not its active site, called the **allosteric site**, and cause a change in the shape of the enzyme, thus affecting the active site. This type of regulation, in which a protein's function at one site is affected by a molecule binding to a separate site, is called **allosteric regulation**. Allosteric regulation may either inhibit or stimulate enzyme activity.

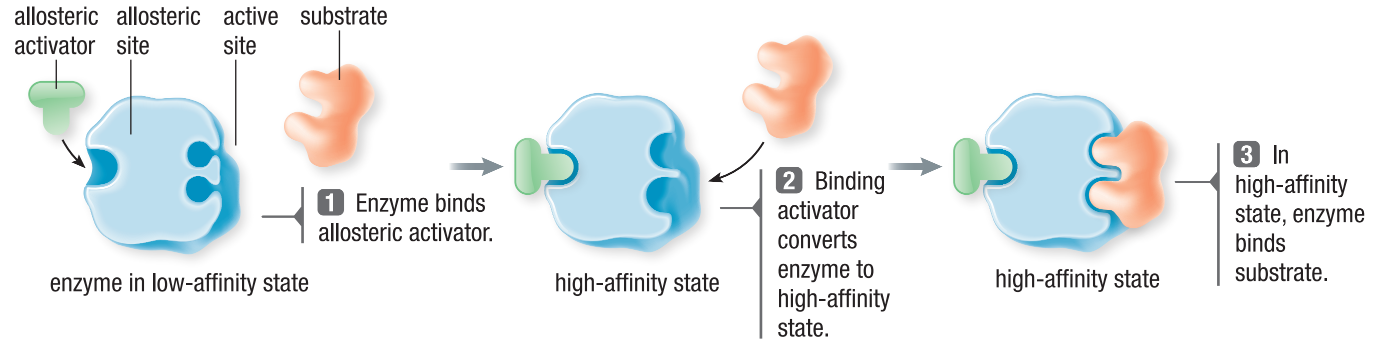
allosteric site a binding site on an enzyme that binds regulatory molecules

allosteric regulation the regulation of one site of a protein by binding to another site on the same protein

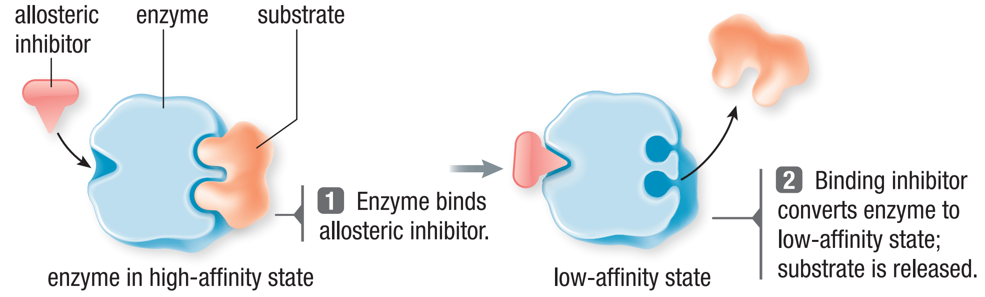
Binding of an allosteric activator molecule stabilizes the enzyme in a shape that causes its active site to have a high affinity for its substrate (**Figure 6(a)**, next page). In this high-affinity state, the enzyme binds its substrate. Conversely, binding of an allosteric inhibitor stabilizes an inactive form of the enzyme. The inhibitor molecule changes the shape of the enzyme in such a way that the substrate is released from the active site (**Figure 6(b)**, next page).

FEEDBACK INHIBITION

Allosteric regulators are important molecules, functioning to control chemical activity in a cell. Frequently, an allosteric inhibitor is a product of the biochemical


allosteric activator
allosteric site
active site
substrate
1 Enzyme binds allosteric activator.
enzyme in low-affinity state
high-affinity state
2 Binding activator converts enzyme to high-affinity state.
high-affinity state
3 In high-affinity state, enzyme binds substrate.

(a) allosteric activation


allosteric inhibitor
enzyme
substrate
1 Enzyme binds allosteric inhibitor.
enzyme in high-affinity state
low-affinity state
2 Binding inhibitor converts enzyme to low-affinity state; substrate is released.

(b) allosteric inhibition

Figure 6 Allosteric regulation includes (a) an allosteric activator, which causes an enzyme to have a high affinity for the substrates it binds, and (b) an allosteric inhibitor, which causes an enzyme to have a low affinity for a substrate, causing its release.

pathway that it regulates. If the product accumulates in excess, its effect as an inhibitor automatically slows or stops the enzymatic reaction that produces it. Usually, it inhibits the enzyme that catalyzes the first reaction of the pathway. If the product is scarce, the inhibition is reduced, and the rate of the reaction increases. Regulation of this type, in which the product of a reaction acts as a regulator of the reaction, is called **feedback inhibition**. Feedback inhibition prevents cellular resources from being wasted in the synthesis of molecules at intermediate steps in the pathway.

feedback inhibition the regulation of a pathway by one of the products of this pathway

The biochemical pathway that makes the amino acid isoleucine from threonine is an example of feedback inhibition. The pathway proceeds in five steps, each catalyzed by a different enzyme (**Figure 7**). The end product of the pathway, isoleucine, is an allosteric inhibitor of the first enzyme in the pathway, threonine deaminase. If the cell makes more isoleucine than it needs, isoleucine combines reversibly with threonine deaminase at the allosteric site. Threonine deaminase is then converted to the low-affinity state, which inhibits its ability to combine with threonine, the substrate for the first reaction in the pathway. If isoleucine levels drop too low, the allosteric site of threonine deaminase is vacated, threonine deaminase converts to the high-affinity state, and isoleucine production increases.

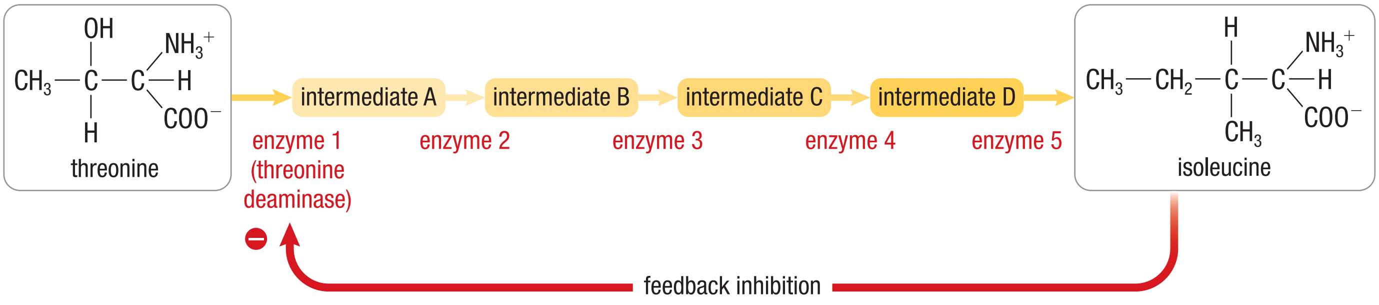


Figure 7 This diagram shows feedback inhibition in the pathway that produces isoleucine from threonine. If the product of the pathway, isoleucine, accumulates in excess, it slows or stops the pathway by acting as an allosteric inhibitor of the enzyme that catalyzes the first step in the pathway.

pH and Temperature Effects on Enzyme Activity

Changes in pH and temperature strongly affect the activity of most enzymes. Enzymes usually reach maximal activity within a narrow range of temperatures and pH values. At levels outside this range, enzyme activity drops off. This usually produces a peaked curve when enzyme activity is plotted, with the peak where temperature and pH produce maximal activity.

Typically, each enzyme has an optimal pH where it operates at its highest efficiency. As the pH either increases or decreases away from its optimal value, the rate of the catalyzed reaction decreases (**Figure 8**). The more the pH value deviates from the optimal value, the more extreme the effects on the structure and function of the active site of the enzyme become, until the rate of the reaction falls to zero. Most enzymes have a pH optimum that is near the pH of their cellular contents, about pH 7. Enzymes that are secreted from cells may have more variable pH optima. Pepsin, for example, a protein-digesting enzyme that is secreted into the stomach, has a pH optimum of 1.5, which is close to the acidity of stomach contents. Similarly, trypsin, a protein-digesting enzyme in the intestine, has a pH optimum of about 8. This allows it to function well in the mildly alkaline contents of the intestine.

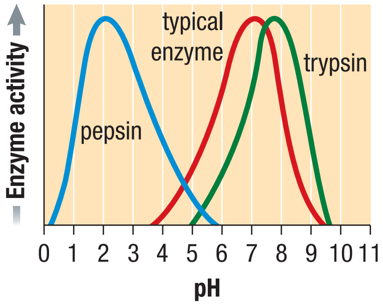


Figure 8 Typical enzymes have an optimal pH value of about 7, but pepsin and trypsin have optimal pH values outside this range.

The effects of temperature changes on enzyme activity reflect two distinct processes. First, temperature has a general effect on all kinds of chemical reactions. As the temperature rises, the rate of a chemical reaction usually increases. This effect reflects increases in the kinetic motion of the molecules. As the temperature rises, there are more frequent and stronger collisions. Second, temperature has an effect on all proteins, including enzymes. As the temperature rises, the kinetic motions of the amino acid chains of an enzyme increase. At the same time, the strength and frequency of the collisions between the enzyme molecules and any surrounding molecules also increases. In the range of 0 to about 40 °C, the reaction rate doubles for every 10 °C increase in temperature (**Figure 9**).

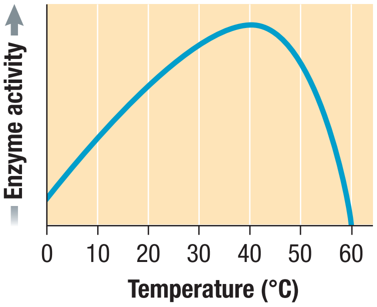


Figure 9 As the temperature increases, the rate of the enzyme-catalyzed reaction increases until the enzyme begins to denature. At this point, the rate of the reaction drops off steeply to zero.

Above 40 °C, the increasing kinetic motion begins to unravel, or denature, an enzyme. The hydrogen bonds and other forces that hold together the enzyme's three-dimensional structure break. As this happens, the enzyme loses its ability to function. The two effects of temperature work in opposition to each other to produce changes in the rate of enzyme activity. The denaturation process reduces the rate of increase in enzyme activity. At some point, as the temperature rises, the reaction rate reaches a peak. Further increases cause unfolding and the reaction rate decreases rapidly to zero.

For most enzymes, the peak in activity lies between 40 °C and 50 °C. The drop-off becomes steep at 55 °C and falls to zero by about 60 °C. The rate of an enzyme-catalyzed reaction peaks at a temperature at which kinetic motion is the greatest but no significant unfolding of the enzyme has occurred. Some enzymes have activity peaks below or above this 40 to 50 °C temperature range. For example, the enzymes of corn pollen function best near 30 °C, and there is a steep reduction in activity above 32 °C. As a result, environmental temperatures above 32 °C inhibit the fertilization of corn crops. Many animals living in frigid regions have enzymes with much lower temperature optima than average. For example, the enzymes of fish in Antarctica are most active near 0 °C. At the other extreme are the enzymes of the single-celled archaea, which live in hot springs. These enzymes are so resistant to denaturation that they remain active at temperatures of 85 °C or more.

Investigation **1.7.1**

Investigating Factors That Affect Enzyme Activity (p. 61)
Certain factors in a reaction's surrounding environment can affect enzyme activity. In this investigation, you will examine the effects of pH and temperature on enzyme activity.

Applications of Enzymes

Milk and other dairy products are recognized as highly nutritious food sources. However, many people suffer from lactose intolerance: the inability to properly break down lactose, the primary disaccharide in milk. For people with lactose intolerance, the problem begins once the lactose passes from the stomach into the small intestine. To absorb the lactose, the digestive cells need to secrete an enzyme called lactase. Lactase catalyzes the efficient breakdown of lactose in the monosaccharides glucose and galactose. People with lactose intolerance do not produce enough lactase, and therefore lactose is not digested or absorbed properly. The lactose is then consumed by bacteria living in the gut, which leads to symptoms including nausea, cramps, and abdominal bloating. Many people overcome this complication by consuming commercial lactase enzymes when they eat dairy products that contain lactose.

Another dairy product, cheese, relies on the enzyme chymosin for its production. Chymosin was originally obtained from the stomach of calves, where it aids in the digestion of milk proteins. This enzyme is now genetically engineered for use in the cheese-making industry. When making cheese, bacteria are added to milk to aid the curdling process. The bacteria feed on the milk and produce lactic acid as a waste product. As the lactic acid is produced, the pH of the milk is lowered and the milk proteins begin to denature. The enzyme chymosin is then added to hydrolyze the most abundant milk protein, casein. The hydrolysis of casein causes the milk to coagulate into semisolid cheese curds. Different types of cheese result from further processing the milk curd. Fat-hydrolyzing enzymes produce cheeses with stronger flavours, such as the Italian cheese Romano.

Industrial food production relies on many types of enzymes. The starch-producing industry is one of the largest users of enzymes. Enzymes break down starch into glucose syrup. Glucose syrup sweetens many foods, medicines, and vitamins. The cleaning industry also relies on enzymes. There are other industrial uses for enzymes. For example, enzymes are added to laundry detergents to improve stain removal. Enzymes are more effective at removing stains such as blood, grass, milk, and perspiration than non-biological chemicals used as cleaning agents. Adding enzymes to detergents removes stains at a lower temperature and with less agitation in a washing machine. Other industrial uses of enzymes are summarized in **Table 1**. CAREER LINK

Table 1 Additional Uses of Enzymes

Product or process	Effects of enzymes
animal feed	degradation of the components of feed to improve nutrient digestion and uses of the feed
brewing	faster maturation of beer; removal of carbohydrates in light beer
dairy	cheese making; removal or conversion of lactose in milk
detergent	breakdown of starch and fatty stains as an active biological component of powder and liquid detergents; colour brightening and softening of cotton garments
leather	unhairing, batting, and defatting; soaking to soften hides and skins
starch	production of glucose, dextrose, fructose, and special syrups for baking and soft-drink production
wine and juice	degradation of the protein pectin for clarification and increase in juice yield

Research This

Researching Enzymes in Industry

Skills: Researching, Evaluating, Communicating

SKILLS HANDBOOK A4.1

There are many commercial applications of enzymes. In this activity, you will research one enzyme that has a commercial application.

1. Choose one of the products listed in Table 1.
2. Research and answer the following questions:

A. What enzymes are used to make this product? T/I

B. What type of reactions do the enzymes catalyze, and why is this of value? T/I

C. What are the sources of the enzymes? T/I

D. Have the enzymes been modified for the process? T/I

E. How are the enzymes regulated? T/I

F. Why are the enzymes not used in the organism or cell where they are naturally found? T/I

G. What careers are associated with the industry that produces the product you chose? T/I

WEB LINK

1.7 Review

Summary

- An enzyme is a biological catalyst with a specific three-dimensional shape, which is necessary for its function. The active site of an enzyme is specific to a particular substrate(s).
- Enzyme activity is affected by substrate and enzyme concentrations, temperature, and pH.
- Competitive inhibitors enter an enzyme's active site to block the binding of the substrate. Noncompetitive inhibitors attach to another site on the enzyme, which changes the shape of the enzyme and its affinity for the substrate.
- Allosteric regulation of enzymes can inhibit or stimulate enzyme activity by altering the affinity of the active site for the substrate.
- Biochemical pathways often use feedback inhibition as a mechanism for regulating the pathway. In negative feedback inhibition, an enzyme involved at the beginning of the pathway is inhibited by a product in the pathway.
- There are many industrial and commercial uses of enzymes.

Questions

1. (a) What is a substrate? What is an active site? How are they related?
   (b) Why is an enzyme considered a biological catalyst? K/U
2. Describe the induced-fit hypothesis of an enzyme-substrate interaction. K/U
3. What is the functional role of a coenzyme or a cofactor in an enzyme-induced reaction? Give an example of an enzyme that requires a cofactor or a coenzyme. K/U
4. Vitamins and their derivatives are important for enzymatic activity and cell metabolism. Research the effects of the absence or overconsumption of one water-soluble vitamin in a diet. Prepare a short report. T/I
5. How does the rate of a reaction change as a result of each of the following factors? Support your answer with a graphic representation of the enzymatic rates. K/U
   (a) enzyme concentration
   (b) substrate concentration
   (c) temperature
   (d) pH
6. Describe noncompetitive enzyme inhibition. Provide an example to support your answer. K/U
7. Malonate is a competitive inhibitor of an enzyme called succinate dehydrogenase. Research this interaction and describe how malonate prevents the enzyme from acting on its substrate, succinate. K/U
8. Describe the different effects of an activator and an inhibitor on an allosterically regulated enzyme. K/U
9. Describe how feedback inhibition reduces the waste of cellular resources. K/U T/I
10. Why is it important for the human body to maintain a proper temperature and a proper pH at all times? K/U
11. You are making a gelatin dessert, but the directions tell you not to use fresh pineapple because the gelatin will not solidify. Gelatin is a structural protein made from collagen. Pineapple contains an enzyme, bromelain, which is a protease. T/I
    (a) What effect does a protease have on a protein like collagen?
    (b) Could you use cooked or canned pineapple instead? Explain your answer.
12. Humans produce enzymes in the mouth, stomach, and small intestine that aid in the process of digestion. As we age, we tend to produce less of these enzymes. What effect could this have on digestion and nutrition? T/I A
13. Digestion cannot take place unless water is present. Explain this statement. T/I

WEB LINK

Investigation 1.5.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Testing for Macromolecules

Consumers are often interested in the chemical composition of products, especially food products. We see food labels that provide data on the carbohydrate, fat, and protein content of foods. (Nucleic acids are not present in significant quantities in food, so they are not included on food labels.) In this investigation, you will use a number of standard tests to identify the three major types of macromolecules in foods. You will use distilled water and a baking soda solution as controls. CAREER LINK

Purpose

To use a set of standardized procedures to test for simple sugars and starch, proteins, and fats

Equipment and Materials

SKILLS HANDBOOK A1

- safety goggles
- lab apron
- 400 mL beaker
- utility stand with ring clamp
- hot plate
- thermometer
- 10 mL graduated cylinder
- test-tube racks
- 8 to 16 test tubes
- test-tube holder
- medicine dropper
- rubber stoppers
- test-tube brush
- depression spot plate
- wax pencil
- known foods: glucose, cornstarch, gelatin, vegetable oil
- unknown food samples
- distilled water
- baking soda solution, 5 %
- glucose solution, 5 %
- cornstarch suspension, 5 %
- detergent solution
- Benedict's reagent
- Lugol's solution
- Sudan IV indicator
- unglazed brown paper
- gelatine solution, 5 %
- Biuret reagent

Benedict's reagent, Lugol's solution, Sudan IV indicator, and Biuret reagent are toxic and can cause an itchy rash. Avoid skin and eye contact. Wash all splashes off your skin and clothing thoroughly. If you get any chemicals in your eyes, rinse with water for at least 15 min and inform your teacher.

Sudan IV indicator is suspended in alcohol, which is flammable. Keep this indicator away from the hot plate.

To unplug the hot plate, pull on the plug, not the cord. Do not touch the hot plate, since it may be very hot.

Procedure

SKILLS HANDBOOK A2.4

1. Put on your safety goggles and lab apron.

Part A: Carbohydrate Test

Benedict's reagent is an indicator that detects the presence of monosaccharides and some disaccharides. **Table 1** shows the colour changes that are observed when a given amount of sugar reacts with Benedict's reagent.

Table 1 Benedict's Reagent

Colour of Benedict's reagent	Approximate sugar concentration (%)
blue	0
light green	0.5–1.5
green to yellow	1.0–2.0
orange	1.5–2.0
red to red brown	> 2.0

2. Pour 300 mL of water into a 400 mL beaker. Secure the beaker in a ring clamp, and place the beaker on a hot plate. Suspend a thermometer in the water, and heat the water to approximately 80 °C.
3. Using a 10 mL graduated cylinder, measure 3 mL of each of the following: distilled water, baking soda solution, glucose solution, starch solution, and each of the known and unknown food samples provided by your teacher. Pour each solution into a clean test tube, and label the test tubes with a wax pencil. Clean the graduated cylinder after pouring each solution.

4. Add 1 mL (15 to 20 drops) of Benedict's reagent to each test tube.
5. Use the test-tube holder to transfer the test tubes to the hot water bath. Observe for 6 min, and record any colour change for each solution.

Lugol's solution contains iodine as an indicator for starch. Iodine turns blue-black in the presence of starch.

6. Using a medicine dropper, place a drop of distilled water and a drop of Lugol's solution on a depression spot plate. Record the colour of the solution.
7. Repeat Step 6, but place a drop of each solution on the spot plate with the drop of Lugol's solution. Record the colour of each solution. Indicate which solutions were positive for the presence of starch. Record your results in a data table.

Part B: Lipid Test

Sudan IV solution can detect the presence of lipids that are soluble in certain solvents. The presence of lipids turns the indicator from a pink to a red colour.

8. Measure 3 mL of each of the following: distilled water, baking soda solution, vegetable oil, and each of the known and unknown food samples. Pour each solution into a clean, labelled test tube. Be sure to clean the graduated cylinder after measuring each sample.
9. Add 6 drops of Sudan IV indicator to each test tube. Place a rubber stopper in each test tube, and shake vigorously for 2 min.

To mix the contents of a stoppered test tube thoroughly, place an index finger on top of the stopper and grip the test tube firmly with your thumb and other fingers. Then shake the test tube, with the top pointed away from you and others.

10. Record the colour of the mixture after 2 min.

Lipids can also be detected using unglazed brown paper. Lipids allow light to be transmitted through the brown paper.

11. Draw a circle, 4 cm in diameter, on a piece of unglazed brown paper for each sample to be tested. Label each circle accordingly.
12. Place a drop of each sample you tested in Step 8 in the appropriately labelled circle.
13. When the water has evaporated from each circle, compare the distilled water sample to each of the other samples by holding the samples up to a light. In your data table, record whether the paper is translucent.

Part C: Protein Test

Biuret reagent can detect the presence of proteins. It reacts with the peptide bonds that join amino acids together, producing the colour changes given in **Table 2**. The + sign indicates the relative amounts of peptide bonds.

Table 2 Biuret Reagent

Colour of Biuret reagent	Relative amount of peptide bonds
blue	no protein
pink	+
violet	++
purple	+++

14. Measure 2 mL of water into a clean, labelled test tube. Repeat with the baking soda and gelatin solutions and each of the known and unknown food samples.
15. Add 2 mL of Biuret reagent to each test tube, and tap the test tube with your fingers to mix the contents. Record any colour changes.

Analyze and Evaluate

(a) What were the dependent and independent variables that you measured and recorded in this investigation? What type of relationship did you test? T/I

(b) How reliable were your results? T/I

(c) Were you surprised by any of your results? If so, which ones? T/I

(d) Which test was most difficult to conduct? Why? T/I

(e) In this investigation, the baking soda solution was used as a "negative control." What do you think this term means? T/I

Apply and Extend

(f) What value is there in knowing the chemical makeup of the foods you eat? T/I

(g) Investigate different food labels to find several foods that have a very high content of one of the three main types of macromolecules (carbohydrates, proteins, or fats). What other substances are listed on a food label? Why is it important to know about the presence of these substances? T/I A

(h) Research the food additives butylated hydroxyanisole (BHA) and butylated hydroxytoluene (BHT). To what types of foods are these chemicals added, and for what purpose? What are some of the potential effects of BHA and BHT on the human body? T/I C

WEB LINK

Investigation 1.5.2 OBSERVATIONAL STUDY

Manipulating Macromolecules

Due to the enormous size and complex shape of many biomolecules, it is not possible or practical to make physical models of them. Some proteins are composed of thousands of atoms, and many nucleic acids are composed of millions of atoms (**Figure 1**). However, these macromolecules can now be displayed and explored using computer-generated models. Computer-modelling technology has greatly enhanced our ability to study macromolecules and gain insight into their functions. In this investigation, you will use sophisticated computer tools to view and manipulate macromolecules.

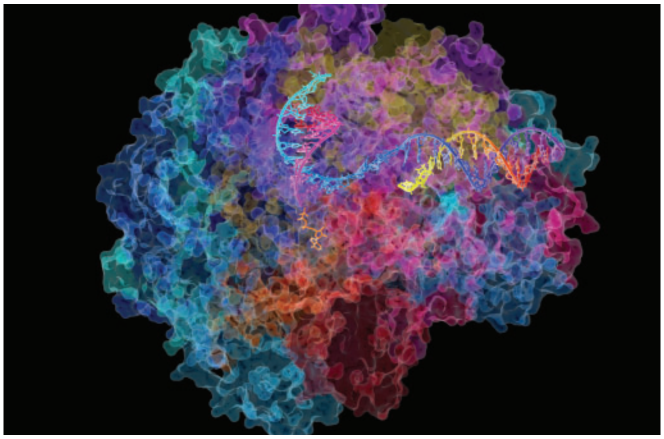


Figure 1 Imaging of RNA polymerase II, a very large protein that is essential for the synthesis of RNA in cells

Purpose

To investigate, observe, and analyze the structural properties and functions of macromolecules using a computer simulation

Equipment and Materials

- computer with Internet access

Procedure

1. Connect to a macromolecule modelling web page through the Nelson Science website.
2. Read the introduction, which describes the software and mouse actions that will allow you to manipulate molecules. When you have finished reading the introduction, move on to explore each type of molecule.

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- **Observing**
- **Analyzing**
- **Evaluating**
- Communicating

3. Complete each of the molecule sections, and answer any questions on the web page and below.

Analyze and Evaluate

(a) Compare mono-, di-, and polysaccharides. Why are all these carbohydrates extremely hydrophilic? Why are not all carbohydrates soluble in water? T/I

(b) Compare the shapes and molecular structures of saturated and unsaturated fatty acids. How do these characteristics influence the properties of the triglycerides in which they are found? T/I

(c) Explore a variety of proteins. T/I

(i) Do all proteins contain α-helixes and β-pleated sheets?

(ii) What holds these secondary structures in place?

(iii) Describe a disulfide bridge. Why is it important in protein structure?

(d) Prepare a table that summarizes your findings about the different properties of carbohydrates, lipids, and proteins in terms of their molecular structure and function. Use the following headings in your table: common functional groups, size, polarity, shape, variability, types of bonding within and between molecules, important functions. T/I C

Apply and Extend

(e) Based on your research on all the different types of protein molecules, explain why protein molecules are the most specialized molecules in the body. T/I A

(f) Considering all of the macromolecules you examined, comment on the relationships between each of the following: T/I

(i) size and solubility

(ii) polarity and solubility

(iii) hydrogen bonding and shape

(iv) shape and function

WEB LINK

Investigation 1.7.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Factors That Affect Enzyme Activity

Enzymes are catalysts that increase the rate of specific reactions in living organisms. Most enzymes are proteins whose performance is dependent on their shape and chemical structure. In this investigation, you will plan and conduct an experiment to test how different environmental conditions affect enzyme activity.

Testable Question

How do changes in temperature, pH, substrate concentration, and enzyme concentration affect the rate of enzyme activity?

Prediction

Based on what you have learned about enzymes and their substrates, write a prediction about how each factor will affect enzyme activity.

Variables

Read the Procedure. Identify all the dependent (responding) and independent (manipulated) variables in this investigation.

Experimental Design

In this investigation, you will design an experiment to test how environmental conditions affect the rate of enzyme activity. Make sure that you include a control. You will use the provided techniques to measure the rate of enzyme activity and display and record all your observations.

Equipment and Materials

SKILLS HANDBOOK A1

- safety goggles
- lab apron
- catalase (liver enzyme)
- hydrogen peroxide (3 %)
- filter paper discs (cut with a hole punch)
- vials
- forceps
- marking pencil
- stopwatch or timer

Hydrogen peroxide is corrosive, and may cause burns to skin, eyes, and respiratory tract. Do not inhale vapours, and be sure to wear safety goggles and gloves.

Procedure

SKILLS HANDBOOK A2.2

Use the following assay in this investigation: A filter paper disc coated with the enzyme catalase will be dropped into a vial containing a solution of the substrate hydrogen peroxide. As the hydrogen peroxide breaks down into water and oxygen gas, bubbles of oxygen will collect on the filter paper so that it rises to the surface of the liquid. The time it takes the filter to rise to the surface will give you an indication of the rate of the enzyme activity.

Focus on one variable (temperature, pH, substrate concentration, or enzyme concentration) for your experiment. Design a procedure to examine the effect of this variable on the rate of catalase activity. List the materials you will need and any safety precautions you must take.

Observations

Once your teacher has approved the materials and procedure you will use, perform your experiment with your lab group. Record the rate of enzyme activity for each trial. Be sure to include a diagram of your experimental setup and all your safety precautions.

Analyze and Evaluate

(a) What variables did you measure, record, and/or manipulate in this investigation? What type of relationship did you test? T/I

(b) Summarize the results of the variables you tested in table or graph format. C

(c) Analyze your results to identify any trends or patterns. T/I

(d) Evaluate your original predictions, taking into account possible sources of error. Draw conclusions based on your data and observations. T/I

(e) Were you able to determine the optimal conditions for a particular factor? Describe your evidence. T/I

(f) Over what range did the enzyme function? T/I

(g) Was there any evidence that the enzyme was denatured under certain conditions? Explain. T/I

(h) Describe ways in which you could improve your procedure and technique. T/I

Apply and Extend

(i) The human body has many enzymes that are catalyzing reactions every second. In this investigation, you learned that environmental conditions are important for enzymes. Research the pH of the body and explain how it is regulated so that enzymes function properly. T/I A

(j) Most enzymes are denatured at high temperatures. How might this be related to the health risks of a high fever when your body temperature reaches 40 °C or higher? T/I

WEB LINK

CHAPTER 1 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 6. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points Questions on page 6. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

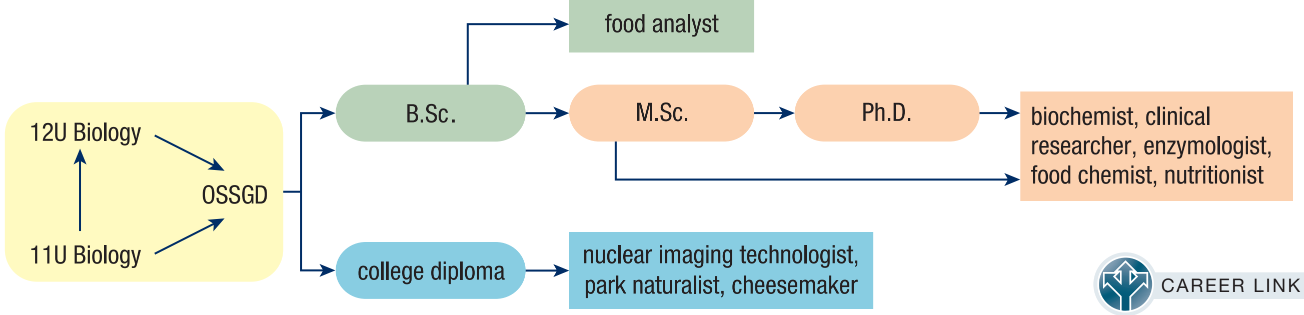
isotope (p. 9)
radioisotope (p. 10)
orbital (p. 11)
valence electron (p. 11)
ionic bond (p. 12)
cation (p. 12)
anion (p. 12)
electronegativity (p. 13)
polar covalent bond (p. 14)
polarity (p. 14)
intermolecular force (p. 15)
van der Waals forces (p. 15)
hydrogen bond (p. 15)
dehydration reaction (p. 16)
hydrolysis reaction (p. 17)
neutralization reaction (p. 17)
redox reaction (p. 17)
oxidation (p. 17)
reduction (p. 17)
specific heat (p. 19)
hydrophilic molecules (p. 21)
hydrophobic molecules (p. 21)
autoionization (p. 21)
buffer (p. 23)
functional group (p. 26)
carbohydrate (p. 29)
monosaccharide (p. 29)
isomer (p. 29)
disaccharide (p. 30)
glycosidic bond (p. 30)
complex carbohydrate (p. 31)
polysaccharide molecule (p. 31)
polymerization (p. 31)
monomer (p. 31)
polymer (p. 31)
lipid (p. 33)
fatty acid (p. 33)
triglyceride (p. 34)
saturated fat (p. 35)
unsaturated fat (p. 35)
phospholipid (p. 35)
steroid (p. 36)
wax (p. 37)
protein (p. 39)
nucleic acid (p. 39)
amino acid (p. 39)
peptide bond (p. 41)
peptide (p. 41)
polypeptide (p. 41)
denaturation (p. 43)
nucleotide (p. 45)
phosphodiester bond (p. 45)
antiparallel (p. 46)
enzyme (p. 50)
substrate (p. 50)
active site (p. 50)
induced-fit model (p. 50)
cofactor (p. 52)
coenzyme (p. 52)
competitive inhibition (p. 53)
noncompetitive inhibition (p. 53)
allosteric site (p. 53)
allosteric regulation (p. 53)
feedback inhibition (p. 54)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers that were mentioned in this chapter.

1. Choose two careers related to the study of macromolecules and enzymes that you find interesting. Research the educational pathway you would need to follow to pursue this career. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers you chose, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.



food analyst
12U Biology
B.Sc.
M.Sc.
Ph.D.
biochemist, clinical researcher, enzymologist, food chemist, nutritionist
OSSGD
11U Biology
college diploma
nuclear imaging technologist, park naturalist, cheesemaker

CAREER LINK

CHAPTER 1 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. In which part of the atom are valence electrons found? (1.1) K/U
   (a) nucleus
   (b) innermost orbital of the element
   (c) outermost orbital of the element
   (d) cannot be determined
2. Which statement about hydrogen bonds is true? (1.1) K/U
   (a) They are stronger than ionic bonds.
   (b) They are stronger than covalent bonds.
   (c) They are weaker than both ionic bonds and covalent bonds.
   (d) They are stronger than both ionic bonds and covalent bonds.
3. Approximately what percentage of human body weight is water? (1.2) K/U
   (a) 23 %
   (b) 35 %
   (c) 60 %
   (d) 97 %
4. Which characteristic of water leads to formation of hydrogen bonds? (1.2) K/U
   (a) density
   (b) crystal structure
   (c) shape
   (d) polarity
5. Which molecule is always a reactant during a hydrolysis reaction? (1.3) K/U
   (a) O_2
   (b) CO_2
   (c) H_2
   (d) H_2O
6. Which property is responsible for the surface tension of water? (1.3) K/U
   (a) mass
   (b) density
   (c) hydrogen bonding
   (d) weak van der Waals' forces
7. Which substance is composed of lipids? (1.4) K/U
   (a) honey
   (b) wood
   (c) oil on feathers
   (d) hair
8. Which type of molecule is used to convey genetic information? (1.5) K/U
   (a) nucleic acid
   (b) protein
   (c) lipid
   (d) carbohydrate
9. When two DNA strands are paired, how are they oriented? (1.5) K/U
   (a) at right angles to each other
   (b) in opposite directions
   (c) at a 45° angle
   (d) in the same direction
10. Which of the following is a function of enzymes? (1.7) K/U
    (a) facilitate digestion
    (b) facilitate light energy reactions in chloroplasts
    (c) allow the reactions in the body to run at a cooler temperature than would otherwise be possible
    (d) all of the above
11. Which statement about an active site on an enzyme is true? (1.7) K/U
    (a) It is only active in acid.
    (b) It is a pocket or groove for binding a substrate.
    (c) It is only operational during rest.
    (d) It is always accompanied by a companion inactive site.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

12. A covalent bond is a shared pair of electrons. (1.1) K/U
13. Water is more dense at −20 °C than it is at 80 °C. (1.2) K/U
14. Hydrogen bonding is responsible for adhesion, which allows a substance to move against gravity in a plant. (1.2) K/U
15. Amino groups are found in all carbohydrates. (1.3) K/U
16. Unsaturated fats stay fluid at lower temperatures than saturated fats do. (1.4) K/U
17. Phosphate groups are acidic and become negatively charged when they lose H^+. (1.5) K/U
18. All proteins are enzymes. (1.5) K/U
19. The enzymes in cells are not dependent on other molecules to function. (1.7) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

Knowledge

For each question, select the best answer from the four alternatives.

1. What is an orbital? (1.1) K/U
   (a) a description of how atoms rotate
   (b) a hard shell that encloses an atom
   (c) a region where electrons are likely to be found
   (d) another name for the nucleus
2. How many bonds does a single nitrogen atom usually form? (1.1) K/U
   (a) none
   (b) one
   (c) two
   (d) three
3. In which food sources are omega-3 fatty acids abundant? (1.1) K/U
   (a) red meat, ocean fish, chicken eggs
   (b) ocean fish, chicken eggs, lake fish
   (c) chicken eggs, lake fish, red meat
   (d) lake fish, red meat, ocean fish
4. Which component or action does a redox reaction always involve? (1.1) K/U
   (a) presence of oxygen
   (b) bonding of a metal to a non-metal
   (c) formation of a solid
   (d) transfer of electrons
5. If the number of neutrons in an atom changes, which of the following is created? (1.1) K/U
   (a) an element
   (b) an anion
   (c) a cation
   (d) an isotope
6. A dehydration synthesis reaction involves which of the following? (1.1) K/U
   (a) the breakdown of molecules with the removal of water
   (b) the formation of large molecules with the removal of water
   (c) the breakdown of large molecules by the addition of water
   (d) the joining of small molecules with the addition of water
7. A large drop of water forms and hangs on the end of a leaky tap for a moment or two before it falls to the ground. Which of the following properties of water are involved in this process? (1.2) K/U
   (a) cohesion and adhesion
   (b) surface tension and cohesion
   (c) adhesion and specific heat
   (d) surface tension and specific heat
8. Which component or action does a neutralization reaction involve? (1.2) K/U
   (a) formation of water
   (b) presence of an acid and a base
   (c) exchange of electrons
   (d) both (a) and (b)
9. Which characteristic of a molecule does a functional group affect in order to increase the solubility of the molecule? (1.3) K/U
   (a) polarity
   (b) molecular mass
   (c) overall shape
   (d) none of the above
10. Which functional group causes ethanol to be polar and also allows it to dissolve in water? (1.3) K/U
    (a) carboxyl
    (b) alcohol
    (c) amino
    (d) phosphate
11. Which substance is not a common source of plant-based simple sugars? (1.4) K/U
    (a) cellulose
    (b) sugar beets
    (c) maple sap
    (d) sugar cane
12. What distinguishes saturated fats from unsaturated fats? (1.4) K/U
    (a) number of carbon atoms
    (b) types of covalent bonds
    (c) presence or absence of oxygen
    (d) shape of the carbon chain
13. Which sugar is a disaccharide? (1.4) K/U
    (a) sucrose
    (b) glucose
    (c) pentose
    (d) hexose

14. Amino acids are to polypeptides as monosaccharides are to which of the following? (1.4) K/U
    (a) nucleic acids
    (b) polysaccharides
    (c) polynucleotides
    (d) disaccharides

15. What do glycosidic bonds link together? (1.4) K/U
    (a) monosaccharides to form disaccharides
    (b) fatty acids and glycerol
    (c) amino acids to form peptides
    (d) phospholipids to form bilayers

16. Which type of molecule is used to convey genetic information? (1.5) K/U
    (a) nucleic acid
    (b) protein
    (c) lipid
    (d) carbohydrate

17. RNA and DNA differ from each other in which way? (1.5) K/U
    (a) RNA has cytosine but DNA does not.
    (b) DNA has ribose but RNA does not.
    (c) DNA has thymine but RNA does not.
    (d) DNA contains nucleotides but RNA does not.

18. What is a function of RNA? (1.5) K/U
    (a) to store genetic information in the nucleus
    (b) to form a permanent bond with DNA
    (c) to copy DNA for protein synthesis
    (d) none of the above

19. After enzymes participate in a reaction, what happens to them? (1.7) K/U
    (a) They must be reactivated.
    (b) They cannot be used again.
    (c) They remain unchanged and can immediately be reused.
    (d) They are consumed and become a new substance.

20. When an enzyme is exposed to extreme changes in pH, its shape and ability to work are affected. What is this process called? (1.7) K/U
    (a) denaturation
    (b) deformation
    (c) deamination
    (d) coagulation

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

21. Radioactivity occurs when an ionic compound decays into ions. (1.1) K/U

22. A bond is more polar when the electronegativity values of the atoms are closer together. (1.1) K/U

23. Water dissociates into H^+ and OH^- ions. (1.2) K/U

24. A buffer is a strong acid or base that can be used effectively to regulate the pH of a solution. (1.2) K/U

25. Hydrogen bonding is partly responsible for the ability of water to dissolve ionic substances in the blood. (1.2) K/U

26. The pH scale represents logarithmic values of the molar concentration of H^+. (1.2) K/U

27. The orientation of the bond between carbon and hydrogen in methane, CH_4, forms 120° angles. (1.3) K/U

28. A gram of fat carries the same energy as a gram of simple sugar. (1.4) K/U

29. Kinks in fat molecules help them stay fluid. (1.4) K/U

30. Cutin is a steroid that prevents water evaporation from the leaves of plants. (1.4) K/U

31. Cutin is a steroid that waterproofs the skins of fruits and vegetables. (1.4) K/U

32. RNA carries the genetic blueprint for viruses. (1.5) K/U

33. Nucleic acids are the most diverse group of biological molecules in human cells. (1.5) K/U

34. In competitive inhibition, a molecule competes with the normal substrate for the active site of an enzyme. (1.7) K/U

35. A cofactor is a non-protein group that binds to a site on an enzyme. (1.7) K/U

36. In noncompetitive inhibition, specific molecules can inhibit enzymes. (1.7) K/U

37. An enzyme can bind with many different substrates. (1.7) K/U

Match each term on the left with the most appropriate description on the right.

38.	(a) ionic bond	(i) interactions between molecules that contain H and N or O
	(b) covalent bond	(ii) bond between charged particles
	(c) hydrogen bond	(iii) weakest intermolecular forces
	(d) van der Waals' forces that are not hydrogen bonds	(iv) sharing of electrons (1.1) K/U
39.	(a) cohesion	(i) temperature moderation
	(b) density	(ii) capillary action
	(c) adhesion	(iii) ice floating on liquid water
	(d) specific heat capacity	(iv) surface tension (1.2) K/U
40.	(a) disaccharide	(i) phosphodiester bond
	(b) protein	(ii) glycosidic link
	(c) DNA	(iii) peptide bond (1.4) K/U

Write a short answer to each question.

41. What are the four elements that make up 96 % of human body mass? (1.1) K/U
42. Distinguish between covalent bonds and intermolecular forces. (1.1) K/U
43. Explain how bonding results in a more stable electron situation for most atoms. (1.1) K/U
44. Define and give an example of a redox reaction. (1.1) K/U
45. What role does the electronegativity of an atom play in the type of bond that it forms? (1.1) K/U
46. In your notebook, copy and complete **Table 1**. Include a definition and an example of each type of substance. (1.2) K/U C

Table 1

	Strong	Weak
Acid		
Base		

47. **Figure 1** shows a water molecule. Explain how the shape of a water molecule relates to its polarity. (1.2) K/U

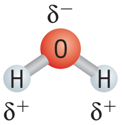


Figure 1

48. List four characteristics of solutions that contain a relatively high concentration of each type of ion. (1.2) K/U
    (a) hydroxide ion
    (b) hydronium ion
49. Which three elements do all four classes of biological molecules contain? (1.3) K/U
50. Identify the six functional groups, and draw the structure of each. (1.3) K/U C
51. List the four main classes of biological molecules. (1.4) K/U
52. Draw and describe a glycosidic bond. (1.4) K/U C
53. (a) Distinguish between α-glucose and β-glucose.
    (b) Which type of biological molecule is each type of glucose found in? (1.4) K/U
54. What is the difference between a triglyceride and a trisaccharide? (1.4) K/U
55. Compare and contrast a monomer and a polymer. (1.4) K/U
56. Use a t-chart to describe the basic characteristics of primary, secondary, tertiary, and quaternary protein structure. (1.5) K/U C
57. Describe a prosthetic group in a protein, and explain what it does. Give an example. (1.5) K/U
58. (a) List the five bases that are found in a nucleic acid.
    (b) What are the other components of a nucleic acid? Sketch an example of a nucleotide that contains them.
    (c) Write a short paragraph, make point-form notes, or sketch a diagram to explain the bonding that occurs between nucleotides when they form a long strand. (1.5) K/U C
59. What is a cofactor? Give one example. (1.7) K/U
60. (a) What is an allosteric site?
    (b) How does allosteric regulation work? (1.7) K/U

Understanding

61. (a) Compare and contrast the characteristics of radioisotopes and stable isotopes.
    (b) What are some potential benefits and risks of exposure to radioisotopes? (1.1) K/U C
62. (a) Explain how the valence electrons in a carbon atom are arranged.
    (b) How does this facilitate the bonding ability of a carbon atom? Illustrate your explanation with sketches. (1.1) K/U T/I C
63. (a) Which elements are most essential to human life and health?
    (b) How can you supply your body with these elements? Give at least three specific examples. (1.1) K/U T/I
64. Explain how the structure of carbon influences the variety of different structures it can form. (1.1) K/U
65. Explain the relationship between polarity and hydrogen bonds. (1.1) K/U
66. Explain five ways that pH has an influence on everyday life. (1.2) K/U A
67. (a) What components must a buffer system contain?
    (b) What is the purpose of a buffer system?
    (c) Give an example of a buffer system. (1.2) K/U
68. Explain the use of polymerization in your body. (1.2) K/U
69. List three characteristics of carbon that make it the backbone of biologically important molecules. (1.3) K/U
70. Explain the difference between a dehydration reaction and a hydrolysis reaction. (1.3) K/U
71. Compare and contrast a glycosidic bond and a peptide bond. (1.3) K/U

72. Use **Figure 2** to answer the following questions. (1.4) K/U

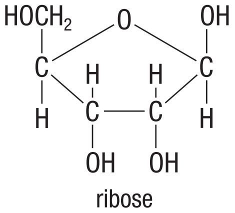


Figure 2

(a) Which type of molecule does this diagram represent?

(b) What is the chemical formula for this molecule?

(c) What group of macromolecules does this molecule belong to?

73. Use a t-chart to distinguish between saturated fats and unsaturated fats. (1.4) K/U C

74. Copy **Table 2** into your notebook. List three types of steroid molecules, and explain their purpose in your body. (1.4) K/U

Table 2

Steroid	Purpose

75. List three types of organisms that produce their own wax, and describe how each type of organism uses the wax produced. (1.4) K/U

76. (a) Discuss the typical sizes of fatty acids.
(b) How does the size of a fatty acid influence its solubility? (1.4) K/U

77. (a) Describe the composition of a phospholipid.
(b) What is the biological importance of phospholipids? (1.4) K/U

78. Create a concept map to describe eight types of proteins and the functions of each type. (1.5) K/U C

79. (a) Compare competitive inhibition and noncompetitive inhibition.
(b) How does each type of inhibition relate to the feedback mechanisms of biological pathways? (1.7) K/U C A

80. Create a flow chart to explain how feedback inhibition works. (1.7) K/U C

Analysis and Application

81. Why do you think the isotopes of an element display the same behaviour in a reaction? (1.1) K/U T/I

82. (a) Draw the lattice structure of ice.
(b) Explain its relevance to a species of fish, such as carp, that lives in lakes. (1.2) K/U C

83. (a) Draw a sketch to show how the hydrophilic and hydrophobic parts of a phospholipid line up in a lipid bilayer membrane.
(b) Explain how the structure of a phospholipid contributes to its function. (1.2) K/U C

84. (a) Describe two unusual properties of water.
(b) How do these properties make water invaluable to life on Earth? (1.2) K/U T/I

85. (a) How would you explain to a parent or guardian the importance of consuming adequate amounts of omega-3 fatty acids?
(b) What type of diet might you suggest to ensure that your parent or guardian consumes adequate amounts of omega-3 fatty acids? (1.4) K/U T/I

86. What is the functional advantage of a fat that has several fatty acid chains, compared with a fat that has only a single fatty acid chain? (1.4) K/U

87. Some people experience "heartburn" when eating fatty, greasy foods (similar to the effect that is felt when eating acidic foods). Why would this occur with fats? (1.4) K/U

88. **Figure 3** shows the general structure of an amino acid. (1.5) K/U T/I

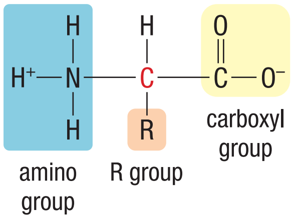


Figure 3

(a) What is an R group, and what is its purpose? Give examples of R groups in the various amino acids.
(b) Which atoms in an amino acid are removed when the amino acid forms a peptide bond?

89. Compare and contrast the structure and function of DNA with the structure and function of RNA. (1.5) K/U T/I

90. **Figure 4** shows two amino acids already joined by a peptide bond. Use diagrams to illustrate how a third amino acid could be attached by dehydration synthesis. (1.5) K/U T/I C

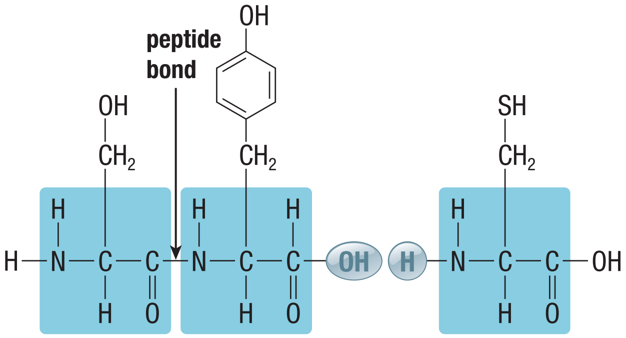


Figure 4

91. Use **Figure 5** to answer the following questions. (1.7) K/U T/I

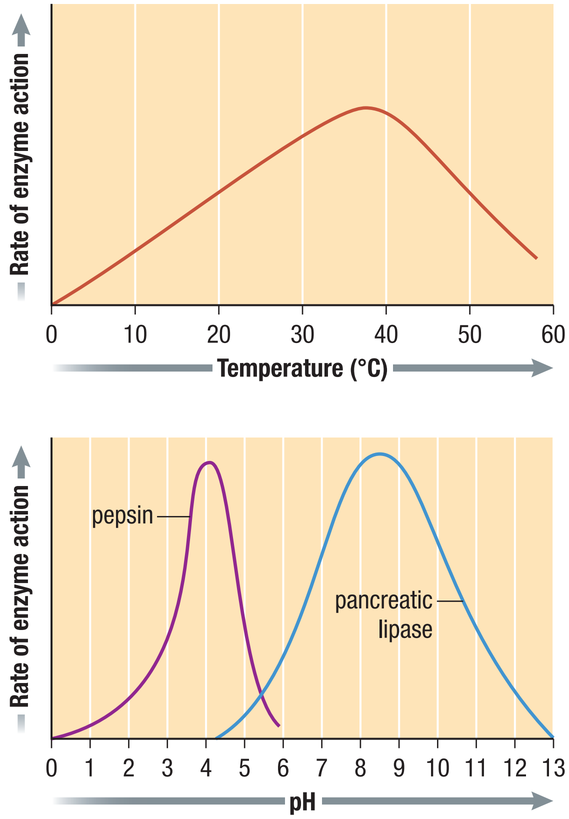


Figure 5

(a) What is the temperature at which maximum enzyme action occurs?

(b) What is the most effective pH value for the enzyme that prefers alkaline (basic) conditions?

(c) What is the most effective pH value for the enzyme that prefers acidic conditions?

92. Is it likely that an enzyme that would catalyze a sugar could also catalyze protein? Explain why or why not. (1.7) K/U

93. Zymase is an enzyme complex that catalyzes the fermentation of sugar into ethanol and carbon dioxide. As this conversion is taking place, the reaction speed gradually decreases. Explain why this happens. (1.7) K/U

Evaluation

94. Water in its solid state is less dense than in its liquid state. How could this property be significant during the winter for organisms that live in lakes and ponds? (1.2) T/I

95. A marathon runner is preparing for a race and needs energy over a sustained period of time. What type(s) of macromolecules should this athlete concentrate on consuming the day or two before the race begins? Explain your reasoning. (1.3) T/I K/U

96. One of the unifying themes in biology is that structure facilitates function at all levels of organization. Explain how the structure of carbohydrates facilitates their function as sources of energy. (1.3) T/I K/U

97. Humans produce cerumen, a waxy secretion, in their outer ears. Based on what you have learned about the characteristics of lipids in this unit, what purpose do you think this serves and why? (1.4) T/I

98. **Figure 6** shows a glucose molecule. During a dehydration reaction between two glucose molecules, water is formed. Can this reaction take place on any of the carbon atoms? Explain. (1.4) T/I C

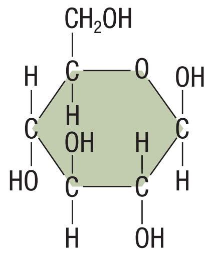


Figure 6

99. In this chapter, you have learned that enzyme activity is affected by substrate and enzyme concentrations, temperature, and pH. Enzyme activity is also affected by water. Why do you think water is an important factor in enzymatic activity? (1.2, 1.7) T/I

100. Based on what you have learned about the effect of temperature on enzymatic activity, why do you think that organs and tissues for transplantation are cooled? (**Figure 7**) (1.7) T/I

Figure 7

101. An industrial company is preparing to use enzymes to carry out a reaction. If you were the scientist planning the reaction, what recommendation for substrate addition would you make to ensure a stable production rate? (1.7) K/U T/I A
102. Suppose that you received a stack of biological sketches of different molecules. You were told that each molecule belongs to one of the following categories: carbohydrates, proteins, nucleic acids, and lipids. How would you sort out the sketches? Explain the clues you would use to distinguish between the groups. (1.7) K/U T/I

Reflect on Your Learning

103. What did you learn about the role of proteins in your body? T/I
104. Explain how knowing about biological molecules can help you make healthy nutrition choices. Will you make any changes to your diet based on what you have learned? C A
105. In this chapter, you learned about basic chemistry and the physics of how water works. Write a paragraph explaining why chemistry and physics have helped you understand biology. A
106. Look back at the diagrams and photographs in this chapter. Write a paragraph about how they helped you understand the molecules and reactions that are essential to life. Then make schematic sketches of the four simple essential molecules: a simple sugar, an amino acid, a lipid, and a nucleic acid. Think about how these molecules are similar and different, and how you can remember their roles. K/U T/I C A
107. Consider the many topics you have studied in this chapter. Choose one topic that you feel has an impact on your life. Write a two-paragraph report about the topic. Why is it important to you? What else would you like to know about the topic? How could you go about learning this? How will it make a practical difference in your life? K/U T/I C A

Research

WEB LINK

108. The radioisotopes that are used in medical diagnosis are not supposed to affect the body. They are usually introduced in a way that will have a minimum effect on the body. For example, radioactive iodine is used as a tracer molecule for the diagnosis of thyroid disease. Iodine gets incorporated into the thyroid hormones. Research more about this process, and explain the mechanism by which iodine leaves the body. T/I A
109. The radioisotopes that are used for cancer treatment are designed to kill cancer cells. However, they usually kill some healthy body cells as well. Examples of chemotherapy isotopes are Co-60, I-131, and Tc-99. Research how these isotopes are used, and prepare a short report to present your findings to the class. T/I C A
110. Research two examples of non-functional enzymes that are involved in the digestion of carbohydrates. Write a brief summary about their effects on the body. T/I
111. Conduct online research to identify the essential fatty acids. Write a brief description of each, including dietary sources. Prepare a dinner menu that includes these dietary sources. T/I C
112. Use the Internet to research the essential amino acids. List these amino acids, and identify dietary sources for each. What is the best way to ensure that all of the essential amino acids are part of your diet? T/I C
113. Research the effects of excess triglyceride consumption on heart health. What can be done to minimize the negative effects of a diet that is high in triglycerides? T/I A

CHAPTER 2

Cell Structure and Function

KEY CONCEPTS

After completing this chapter you will be able to

- recognize the difference between prokaryotic cells and eukaryotic cells
- describe the different components of a cell and how each component functions
- explain how molecules move across cell membranes via different forms of transport
- explain what factors affect the transport of molecules across cell and organelle membranes

What Are the Different Components of a Cell and How Do They Function?

As you read this chapter, your eyes are moving, your heart is beating, and your brain is interpreting the words you see. There is a lot going on, and many different body parts are working simultaneously. The cells in your body are organized into tissues, organs, and organ systems. By coordinating their actions and communicating with each other, your cells enable you to read this chapter.

Each of the approximately 50 trillion to 75 trillion cells that form your body has a specific role. For example, red blood cells transport oxygen, muscle cells contract and allow you to move, nerve cells send and receive messages as electrical impulses, and liver cells break down toxins. Different types of cells are different sizes, but all of them are small. Red blood cells measure 8 μm in diameter. They are so small that 1 mL of blood can contain 5 billion or more of them. A human egg cell is the largest human cell. It measures 130 μm in diameter and is about one-fiftieth the volume of a single grain of table salt.

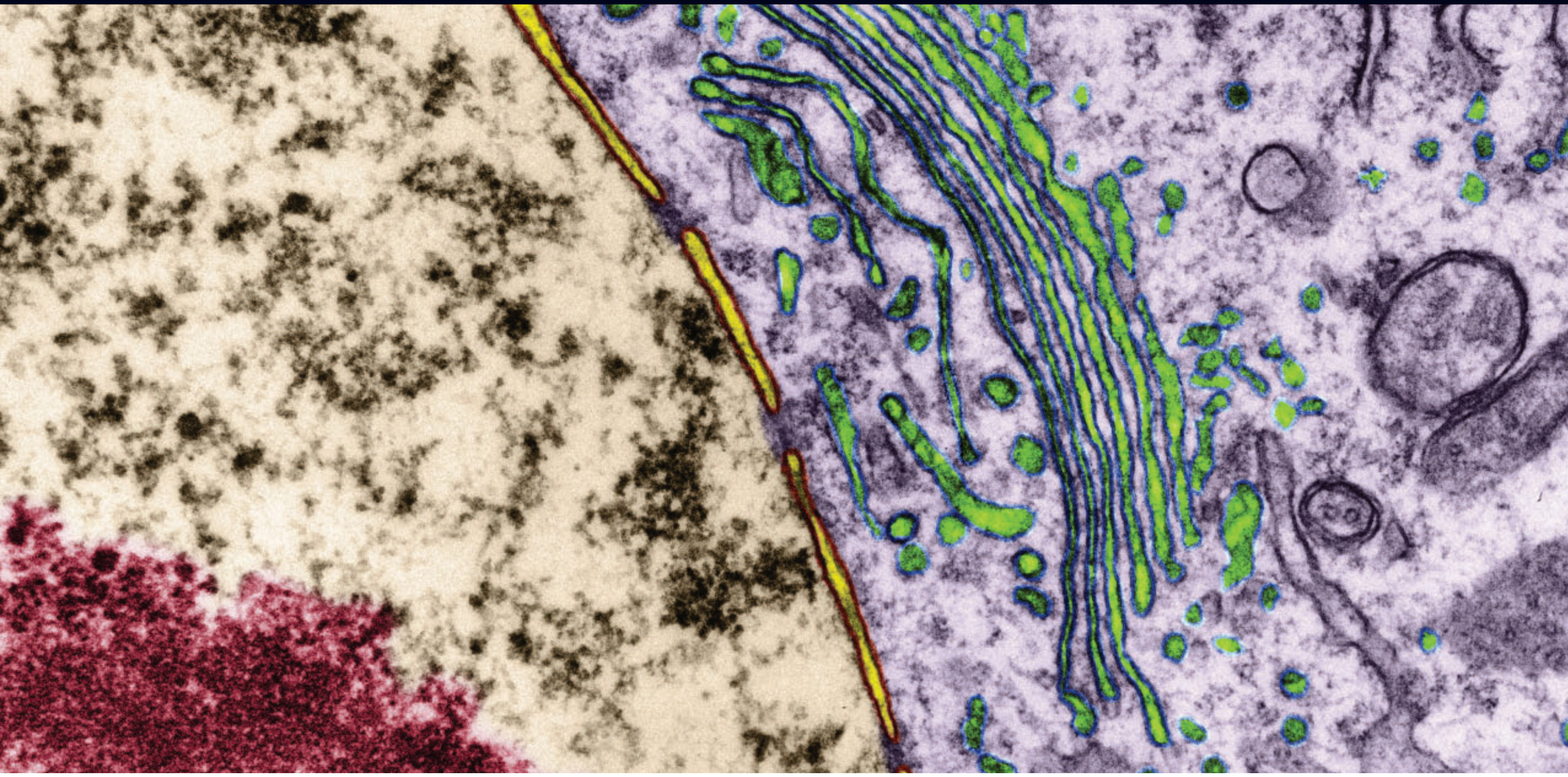
Using an electron microscope, scientists can observe the fine infrastructure of cells and examine their many different components. These components are formed from or contain the compounds you learned about in Chapter 1. For example, the internal fibres are formed from long proteins, the small organelles store and digest carbohydrates and lipids using enzymes, and the nucleus houses long strands of nucleic acid. The internal structure of a cell provides clues as to its function. For example, large numbers of mitochondria are found in heart muscle cells that perform a very energy-demanding task, whereas large numbers of ribosomes are found in pancreas cells whose main role is to produce large quantities of the hormone insulin—a protein. Look at the image of a cell on the next page. It is hard to imagine that something so small can be so beautiful and complex.

In this chapter, you will explore the structures and functions of the many components of the cell. You will learn how each component helps the cell function on its own and in relation to other cells.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Simply put, a cell is a container.
   (a) What are the properties of a container?
   (b) What are the advantages of a container having rigid sides? What about flexible sides?
   (c) Do you know of any containers that can hold a liquid while allowing other materials to pass in and out?
2. Containers are made of all types of materials, from thick rigid glass to thin flexible plastic. When you blow a bubble with soapy water, you are creating a gas-filled container with liquid walls. What types of materials would you expect to find in the membranes of a living cell? What properties do you think these materials would have?
3. Based on what you learned in Chapter 1, what types of molecules do you think could or could not easily enter or exit through a cell membrane? Consider size, polarity, and other properties.



Mini **Investigation**

Observing Osmosis—Seeing Red

Skills: Performing, Observing, Analyzing SKILLS HANDBOOK A2.1

A plant cell has an outer wall that helps to maintain its structure while letting water diffuse in and out of the plasma membrane. In this activity, you will place red onion cells in different solutions and observe how the diffusion of water through the plasma membrane changes the volume of the cells.

Equipment and Materials: scissors; forceps; two slides with cover slips; microscope; red onion; 5 % salt solution in a dropper bottle; paper towels; distilled water in a dropper bottle

1. Use the scissors to cut a small piece of red onion. Using forceps, peel off a single layer of red pigmented cells.
2. Make a wet mount using distilled water and view the red onion cells under the microscope. Record the shape and form of the cells.
3. Add a few drops of salt solution to the edge of the cover slip. Then draw the salt solution under the cover slip by using a paper towel to wick away water from the other side of the cover slip.
4. View the cells under the microscope again. Continue viewing for 5 min or until you notice a significant change in the appearance of the cells. Make a sketch of any changes you observe.
5. Repeat Step 3 using distilled water to displace the added salt solution. View the cells under the microscope again. Continue viewing for 5 min or until the cells have returned to their original appearance. Record your observations.

A. What was the shape of the onion cells in the wet mount before you added the salt solution? Where within the cytosol was the red pigment located? T/I

B. What happened to the shape of the cells after you added the salt solution? In your sketch, label the places where the cells “pulled away” from their cell wall. Describe any changes in the colour of the cells. Explain what caused these changes to occur. T/I C

C. What happened to the cells when distilled water was added to the slide? Compare this slide with your first slide. What caused the changes, and what role did the cell wall play? T/I

2.1

Cell Structures

The internal structures of a cell interact and complement each other in both form and function. In eukaryotic cells, internal structures, or **organelles**, carry out specialized functions. Some organelles isolate toxic or harmful substances from the rest of the cell or provide a favourable environment for a reaction that could not occur in the cytosol. Other organelles transport substances through the cytosol, maintaining the fluid balance. The shapes of some organelles are quite elaborate, because each organelle is adapted to perform a specific function.

organelle an internal functional structure that is located within the cytosol of a cell

LEARNING **TIP**

Cytoplasm versus Cytosol

The term "cytoplasm" is often used to refer to the liquid portion of the cell, but the more precise term is "cytosol." Cell biologists use "cytoplasm" to refer to *all* of the internal components of the cell, other than the nucleus.

In this section, you will focus on the organelles inside eukaryotic plant and animal cells. Plant cells differ from animal cells because plants and animals have very different requirements for obtaining food and energy. Although fungi are not discussed in this section, they have many of the same organelles that plants and animals have. Fungi-like animals are heterotrophic, while the protist kingdom includes both heterotrophs and photosynthetic autotrophs. The most complex of all cells are those of some single-celled protists.

The cell itself, and many organelles within it, are bounded by membranes that control the amounts and types of substances that move in and out of the cell or organelle. The **plasma membrane** forms a barrier around the cytosol of the cell. The membrane surrounding an organelle maintains an internal environment that allows the organelle to carry out its particular function.

plasma membrane a dynamic barrier that surrounds the cytosol of the cell

An organelle rarely works alone. Just as your organ systems work together to keep your body functioning, it takes a team of organelles to keep a cell running. Substances move between different organelles and the plasma membrane. Some metabolic pathways take place in a series of different organelles. At the same time, the cell needs to reproduce itself to generate more cells. **Figure 1** and **Table 1** (next page) show the common components of a eukaryotic cell. You can refer back to Figure 1 and Table 1 as you read about the specific organelles.

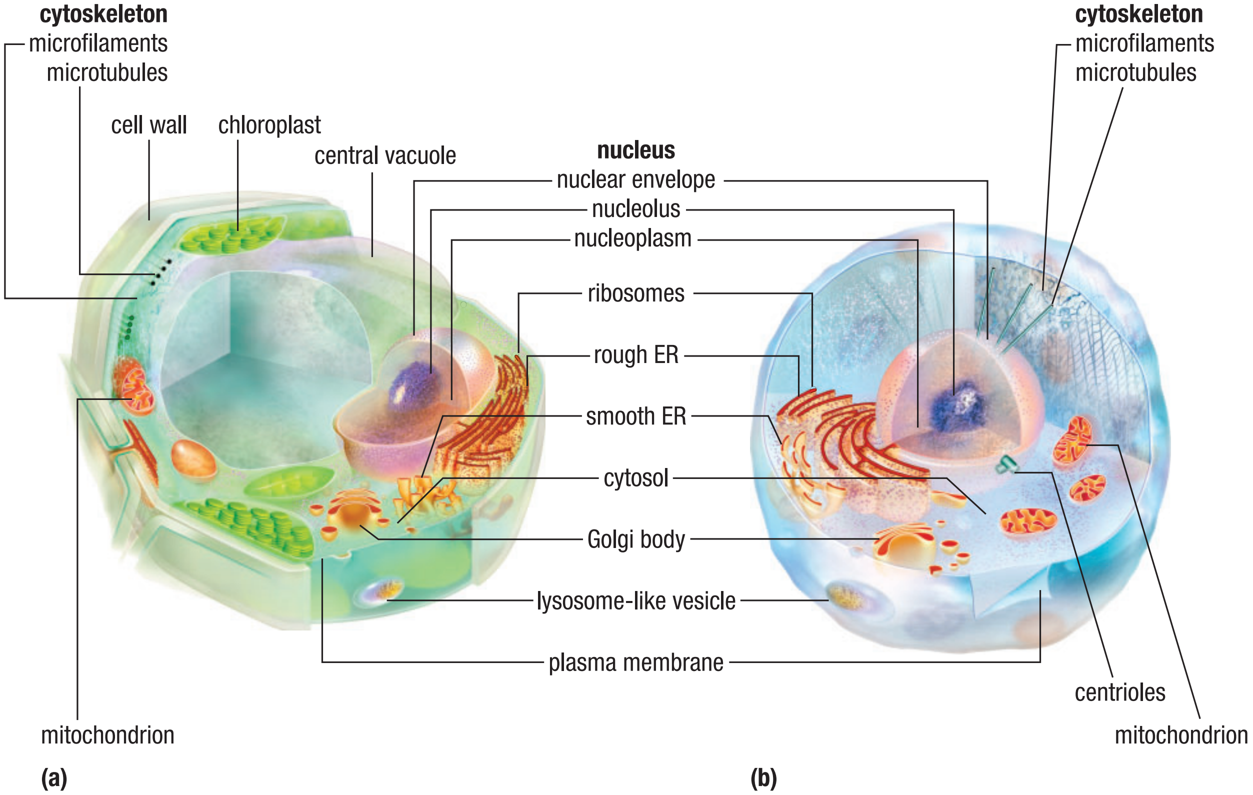


Figure 1 The functions of the organelles of (a) a typical plant cell and (b) a typical animal cell are described in Table 1.

The Nucleus

Almost all eukaryotic cells have a nucleus. The nucleus is an organelle that contains almost all the DNA in a eukaryotic cell. Small amounts of DNA are present in two other organelles that you will learn about later—chloroplasts and mitochondria. The nucleus protects the DNA, or genetic material, in the cell. Isolated in its own compartment, the DNA stays separated from the activity of the cytosol and from the metabolic reactions that might damage it.

Nuclear Envelope

The nucleus is surrounded by a double membrane called the nuclear membrane or **nuclear envelope**. It consists of two lipid bilayers that are folded together. The outer bilayer of the membrane is continuous with the membrane of another organelle, the endoplasmic reticulum (ER). Different kinds of membrane proteins are embedded in the two lipid bilayers. Some are receptors and transporters. Others collect in tiny pores that span the membrane (**Figure 2**). The membrane proteins work with the lipid bilayers, as a system, to transport various molecules across the nuclear membrane.

nuclear envelope a two-layer membrane that encloses the nucleus of a eukaryotic cell

Like other membranes, the nuclear envelope allows water and gases to cross freely. Other substances can only enter and exit the nucleus with the help of a system of transporters and pumps that span the nuclear envelope. The system of transporters and pumps controls the passage of molecules between the nucleus and the cytosol. For example, cells access their DNA when they make RNA and proteins, so various molecules that are involved in this process must pass into and out of the nucleus. The nuclear membrane allows only certain molecules to cross it, at certain times and in certain amounts. This control is another measure of safety for the DNA, as well as a way for the cell to regulate the production of RNA and proteins.

Proteins that attach to the inner surface of the nuclear envelope anchor the DNA molecules and keep them organized. During cell division (mitosis), these proteins help the cell pass DNA to its two daughter cells. You will learn more about transport across membranes in Section 2.4.

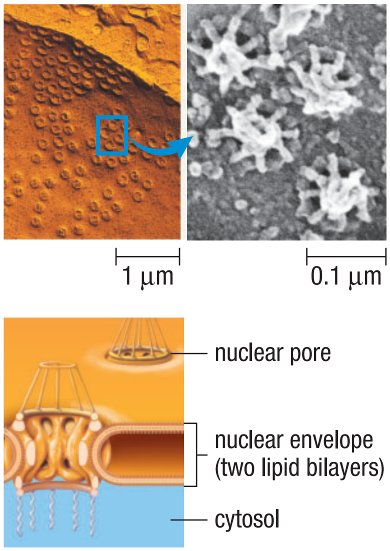


Figure 2 The structure of a nuclear pore

Table 1 Organelles of Eukaryotic Cells

Category	Name	Primary function(s)
Organelles with a membrane	nucleus	protects and controls access to the DNA; makes ribosome subunits
	endoplasmic reticulum (ER)	routes and modifies new polypeptide chains; synthesizes lipids
	Golgi body	modifies new polypeptide chains; sorts and ships proteins and lipids
	transport/secretory vesicle	transports substances within a cell and or releases them from the cell
	mitochondrion	generates ATP and other molecules
	chloroplast	produces sugars using light energy, carbon dioxide, and water
	lysosome	carries out intracellular digestion
	peroxisome	inactivates toxins
	vacuole	provides storage and contains waste; in plants, maintains cell size and shape
Organelles without a membrane	ribosome	assembles polypeptide chains that are used to form proteins
	centriole	makes microtubules for the cytoskeleton; involved in cell division

Nucleolus

Enclosed by the nuclear envelope, the nucleus contains nucleoplasm, which is a viscous fluid that is similar to cytosol. The nucleus also contains at least one nucleolus (plural: nucleoli), a dense irregularly shaped region where subunits of ribosomes are assembled from proteins and RNA. **Figure 3** shows the components of the nucleus.

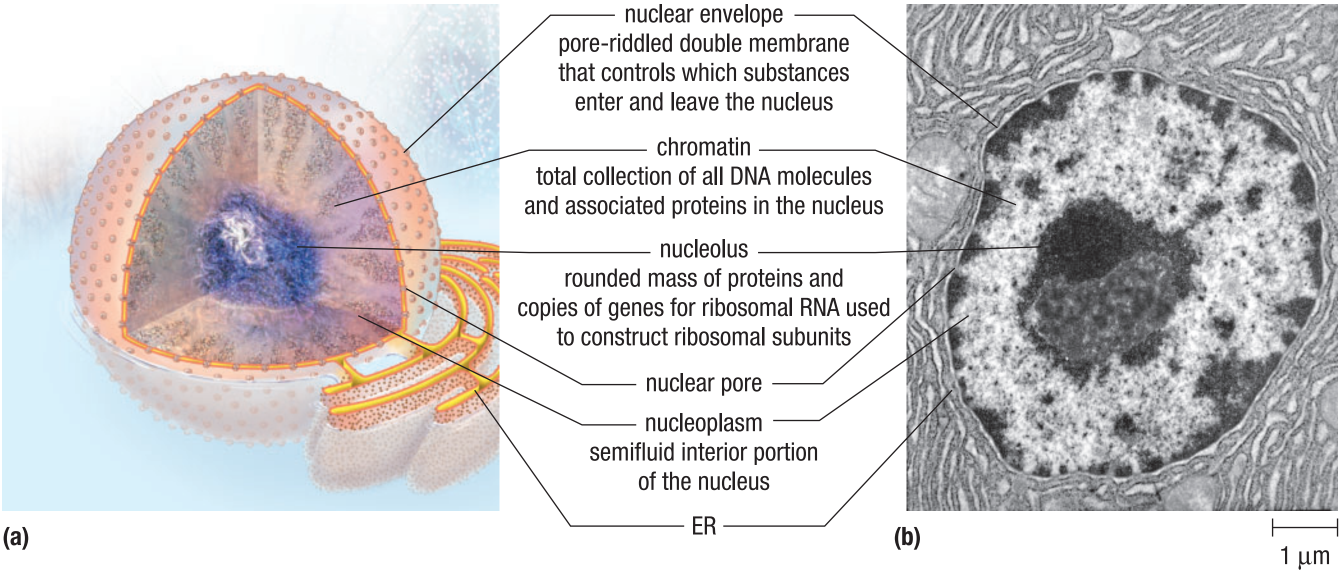

nuclear envelope
pore-riddled double membrane that controls which substances enter and leave the nucleus
chromatin
total collection of all DNA molecules and associated proteins in the nucleus
nucleolus
rounded mass of proteins and copies of genes for ribosomal RNA used to construct ribosomal subunits
nuclear pore
nucleoplasm
semifluid interior portion of the nucleus
ER
(a)
(b)
1 μm

Figure 3 (a) A diagram of a nucleus and (b) transmission electron microscopy (TEM) showing the nucleus of a cell from the pancreas of a mouse

The Endomembrane System

endomembrane system a group of interacting organelles between the nucleus and the plasma membrane

The **endomembrane system** is a group of interacting organelles between the nucleus and the plasma membrane (**Figure 4**). Its main function is to make lipids, enzymes, and other proteins for secretion or insertion into cell membranes. It also has other specialized functions, such as destroying toxins and recycling wastes. The components of the endomembrane system vary among different types of cells, but the most common components are described in the following text and in **Figure 5**.

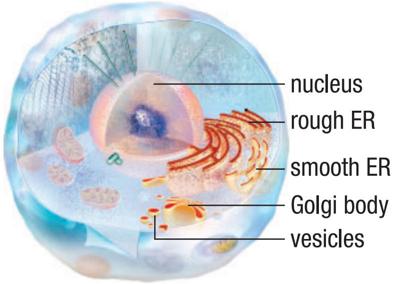
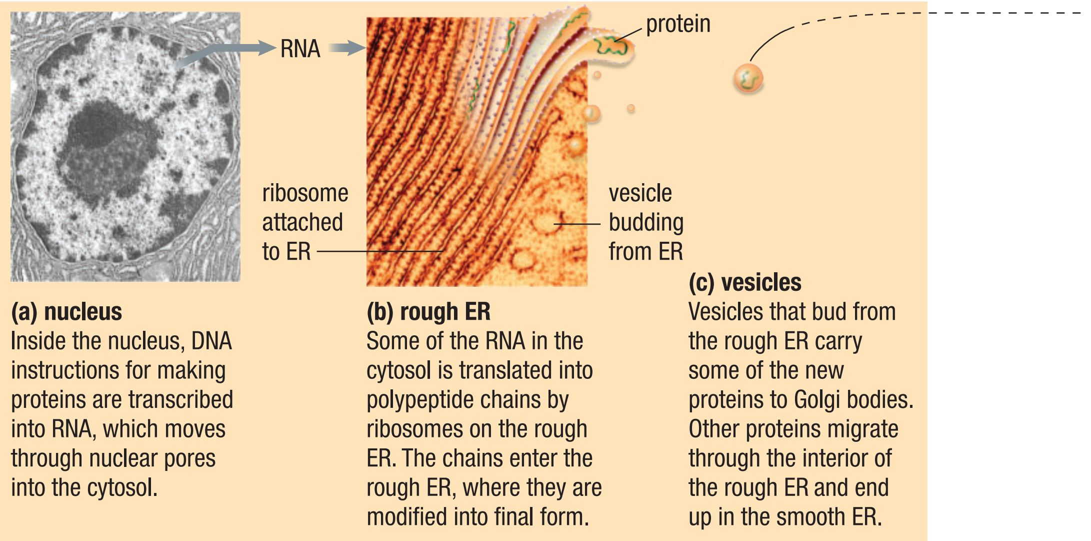


Figure 4 Components of the endomembrane system



(a) nucleus
Inside the nucleus, DNA instructions for making proteins are transcribed into RNA, which moves through nuclear pores into the cytosol.

(b) rough ER
Some of the RNA in the cytosol is translated into polypeptide chains by ribosomes on the rough ER. The chains enter the rough ER, where they are modified into final form.

(c) vesicles
Vesicles that bud from the rough ER carry some of the new proteins to Golgi bodies. Other proteins migrate through the interior of the rough ER and end up in the smooth ER.

Figure 5 The endomembrane system builds lipids and many proteins, which are transported to other cellular destinations or to the plasma membrane.

Endoplasmic Reticulum

The **endoplasmic reticulum (ER)** is an extension of the nuclear envelope (Figure 5(a)). It forms a continuous compartment that folds repeatedly into flattened sacs and tubes. Two kinds of ER—rough ER and smooth ER—are named for their appearance in electron micrographs. Many thousands of ribosomes are attached to the outer surface of **rough ER** (Figure 5(b)). The ribosomes synthesize polypeptide chains, which are released into the interior of the ER. Inside the ER, the proteins fold and take on their complex structure. Some of the proteins become part of the ER membrane itself, whereas other proteins are carried to different destinations in the cell. Cells that make, store, and secrete a lot of proteins have a lot of rough ER. For example, ER-rich gland cells in the pancreas make and secrete enzymes that help to digest food in the small intestine.

endoplasmic reticulum (ER) a membrane-bound organelle that is folded into flattened sacs and tubes, and is often an outgrowth of the nuclear envelope in a eukaryotic cell

rough ER areas of endoplasmic reticulum with ribosomes attached to the surface

Smooth ER has no ribosomes, so it does not make proteins. Some of the polypeptides that are made in the rough ER end up in the smooth ER as enzymes (Figure 5(d)). These enzymes produce most of the cell's membrane lipids. They also break down carbohydrates, fatty acids, and some drugs and poisons.

smooth ER areas of the endoplasmic reticulum without attached ribosomes

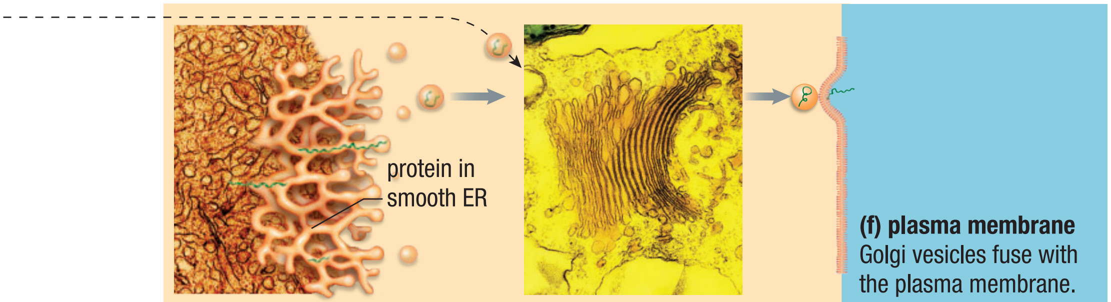
Vesicles

Vesicles are membrane-enclosed, saclike organelles (Figure 5(c)). They form in great numbers, either on their own or by budding from other organelles or from the plasma membrane. There are many types of vesicles with many different functions. Some types transport proteins from one organelle to another, or to and from the plasma membrane. Another type, called a peroxisome, contains enzymes that digest fatty acids and amino acids. Peroxisomes form and divide on their own and have a variety of functions, such as inactivating hydrogen peroxide, a toxic by-product of fatty acid breakdown. Enzymes, such as catalase, in the peroxisomes convert hydrogen peroxide to water and oxygen, or they use hydrogen peroxide in reactions that break down alcohol and other toxins.

vesicle a small, membrane-bound organelle that may transport, store, or digest substances within a cell

Plant and animal cells contain vesicles called **vacuoles**. Although vacuoles appear empty under a microscope, they serve an important function—they are like trash cans. They isolate and dispose of wastes, debris, and toxic materials. A large central vacuole is present in plant cells. Amino acids, sugars, ions, wastes, and toxins accumulate in the water-filled interior of the central vacuole. Fluid pressure in the central vacuole keeps the plant cell, and therefore structures such as stems and leaves, firm. Usually, the central vacuole takes up 50 to 90 % of the cell's interior, with the cytosol confined to the narrow area between this large organelle and the plasma membrane.

vacuole a liquid-filled organelle that stores waste and aids in cellular metabolism and water balance



(d) smooth ER
Some proteins from the rough ER are packaged into new vesicles and shipped to the Golgi bodies. Others become enzymes of the ER that assemble lipids or inactivate toxins.

(e) Golgi body
Proteins arriving in vesicles from the ER are modified into final form and sorted. New vesicles carry them to the plasma membrane or to lysosomes.

(f) plasma membrane
Golgi vesicles fuse with the plasma membrane. Lipids and proteins of a vesicle's membrane fuse with the plasma membrane, and the vesicle's contents are released to the exterior of the cell.

lysosome a small, membrane-bound organelle that contains digestive enzymes that aid in waste disposal

Lysosomes are vesicles that contain powerful digestive enzymes. They fuse with vacuoles that carry particles or molecules for disposal, such as worn-out cell components. Lysosomal enzymes empty into these vacuoles and digest their contents.

Golgi Bodies

Golgi body an organelle with folded membranes where the final packaging of proteins occurs

Many vesicles fuse with and empty their contents into a **Golgi body** (Figure 5(e)). This organelle has a folded membrane that usually looks like a stack of pancakes. Enzymes in a Golgi body put finishing touches on polypeptide chains and lipids that have been delivered from the ER. They attach phosphate groups or sugars, and they cleave certain polypeptide chains. The end products—membrane proteins, proteins for secretion, and enzymes—are sorted and packaged into new vesicles that carry them to the plasma membrane or to lysosomes (Figure 5(f)).

Other Organelles

Eukaryotic cells have other organelles, in addition to those described above. For example, nearly all eukaryotic cells make most of their ATP in mitochondria. In addition, plants and some types of algae have special organelles called plastids that are used for storage and photosynthesis.

Mitochondria

mitochondrion an organelle with two membranes; the site of most ATP synthesis during aerobic cellular respiration

The **mitochondrion** (plural: mitochondria) is a type of organelle that specializes in making ATP (**Figure 6**). Nearly all eukaryotic cells have mitochondria, but prokaryotes do not. In plants and animals, most ATP is produced in a series of reactions that occur inside the mitochondria and require oxygen (Chapter 4). These reactions can extract more energy from organic compounds than any other metabolic pathway. With each breath, you take in oxygen that is used by the mitochondria in your trillions of energy-demanding cells.

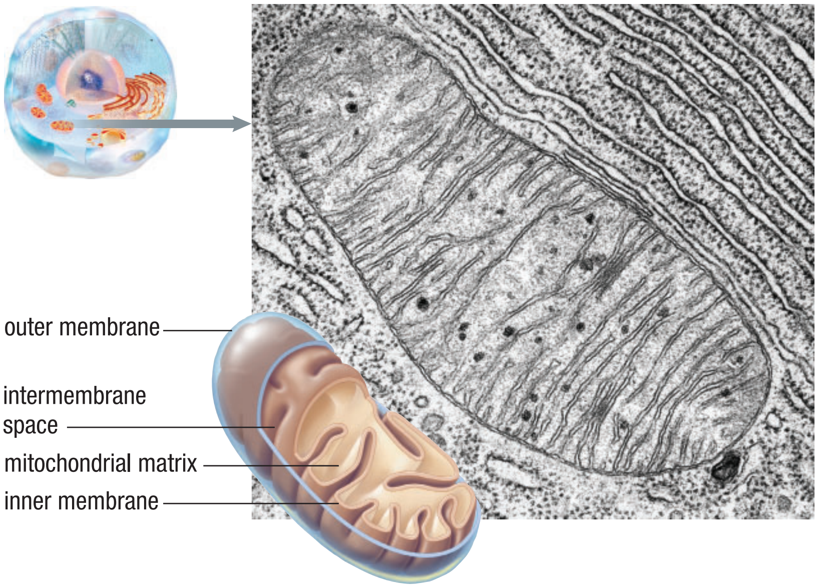


Figure 6 A sketch and a transmission electron micrograph of a mitochondrion. This organelle specializes in producing large quantities of ATP.

The number of mitochondria varies based on the type of cell and the type of organism. For example, a single-celled yeast (a type of fungus) may have only one mitochondrion, whereas a human skeletal muscle cell may have a thousand or more. Cells that have a very high demand for energy tend to have many mitochondria.

Typical mitochondria are between 1 and 4 μm in length, but a few are as long as 10 μm. Some mitochondria are branched. These organelles can change shape, split in two, and fuse together. A mitochondrion has two membranes, one highly folded inside the other. This arrangement creates two compartments: the mitochondrial matrix (the interior of the mitochondrion) and the intermembrane space (the space between the two mitochondrial membranes).

Mitochondria resemble bacteria in size, form, and biochemistry. They have their own DNA, which is similar to bacterial DNA. They divide independently of the cell and have their own ribosomes. Such clues led to the now widely accepted theory of endosymbiosis. According to this theory, mitochondria evolved from aerobic bacteria that took up permanent residence inside a host cell.

Plastids

Plastids are membrane-enclosed organelles that are used for photosynthesis or storage in plants and algal cells. Chloroplasts, chromoplasts, and amyloplasts are common types of plastids. Photosynthetic cells of plants and many protists contain **chloroplasts**, which are organelles that are specialized for photosynthesis (Chapter 5). Most chloroplasts are an oval or disk shape. Two outer membranes enclose a semifluid interior called the stroma (**Figure 7**). The stroma contains enzymes and the chloroplast's DNA. Inside the stroma, a third highly folded membrane forms a single compartment. In many ways, chloroplasts resemble photosynthetic bacteria. Like mitochondria, they may have evolved by endosymbiosis.

plastid a membrane-bound organelle that is involved in photosynthesis and storage in plants and algae

chloroplast a double-membrane-bound organelle that contains enzymes and pigments that are used to perform photosynthesis in eukaryotic cells

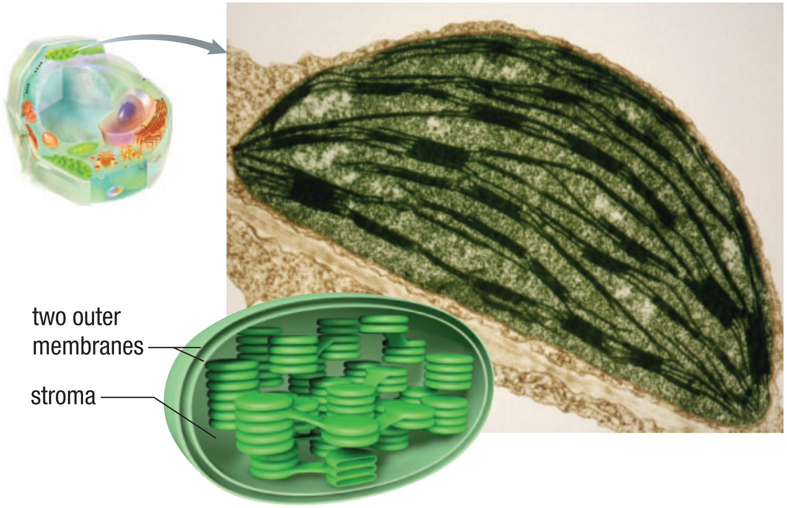


Figure 7 The chloroplast is a defining component in photosynthetic eukaryotic cells. This transmission electron micrograph shows a chloroplast from a tobacco leaf (*Nicotiana tabacum*). The lighter patches are nucleoids, where DNA is stored.

Chromoplasts make and store pigments other than chlorophyll. They have an abundance of orange and red carotenoids, the pigments that colour many flowers, leaves, fruits, and roots. These colourful pigments are revealed in the autumn, when the chlorophyll in some plant leaves is broken down and the bright fall colours of yellows, oranges, and reds are visible. The carotenoids are also visible in fruits. For example, as a tomato ripens, its green chloroplasts are converted to red chromoplasts, and its colour changes. **Amyloplasts** are unpigmented plastids that often store starch grains. They are abundant in the cells of stems, tubers (underground stems), and seeds. In some plant cells, amyloplasts function as gravity-sensing organelles.

chromoplast an organelle that makes and stores pigments other than chlorophyll

amyloplast an organelle that stores starch

The Dynamic Cytoskeleton

Between the nucleus and plasma membrane of a eukaryotic cell is a **cytoskeleton**: an interconnected system of many protein filaments. Parts of the cytoskeleton reinforce, organize, and move cell structures, and often the whole cell. Some cytoskeleton structures are permanent, whereas others only form at certain times.

cytoskeleton a dynamic system of filaments that provides cell structure, helps with cell division, and enables the cell and inner organelles to move around

Microtubules and Microfilaments

A microtubule is a long, hollow cylinder that consists of subunits of the protein tubulin. Microtubules form a dynamic scaffolding for many cellular processes, rapidly assembling when they are needed and disassembling when they are not. For example, some microtubules assemble before a eukaryotic cell divides, separate the cell's duplicated chromosomes, and then disassemble.

microfilament a fibre structure made from actin that is part of the cytoskeleton and is located in the cytosol of cells

A **microfilament** is a fibre that consists primarily of subunits of the protein actin. Microfilaments strengthen or change the shape of eukaryotic cells. Actin microfilaments, which form at the edge of a cell, drag or extend it in a certain direction (**Figure 8**). In muscle cells, microfilaments of myosin and actin interact to bring about contraction.

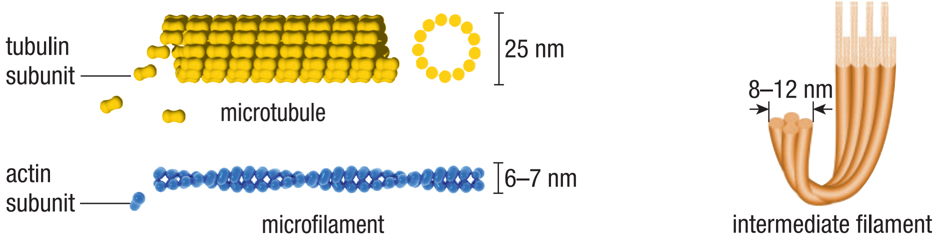


Figure 8 Components of the cytoskeleton

Intermediate filaments are the most stable part of a cell's cytoskeleton. They consist of fibrous proteins, each with a globular head and tail and a rodlike centre. Intermediate filaments strengthen and maintain cell and tissue structures and are the toughest of the cytoskeleton filaments. They are in the cytosol and nucleus of most animal cells.

Cilia, Flagella, and Pseudopods

flagellum a whiplike tail that is used in propulsion of both prokaryotic and eukaryotic cells

cilia tiny hairlike structures that move water and mucus in eukaryotes; used for movement of prokaryotic cells

Organized arrays of microtubules are found in eukaryotic flagella (singular: flagellum) and cilia (singular: cilium) (**Figure 9(a)** and **(b)**). **Flagella**, whiplike structures that propel cells such as sperm through fluid, tend to be longer and less abundant than cilia. The coordinated beating of **cilia** propels motile cells through fluid and stirs fluid around stationary cells. For example, the coordinated motion of cilia on the thousands of cells that line your airways sweeps particles away from your lungs.

A special array of microtubules extends lengthwise through a flagellum or a cilium. Protein spokes and links stabilize the array. The microtubules grow from a barrel-shaped organelle called a centriole, which remains located below the array after it forms. Amoebas and other types of eukaryotic cells form lobes called pseudopods or "false feet" (**Figure 9(c)**). As these temporary irregular lobes bulge outward, they move the cell and engulf a target, such as prey. Elongated microfilaments force the lobes to advance in a steady direction.

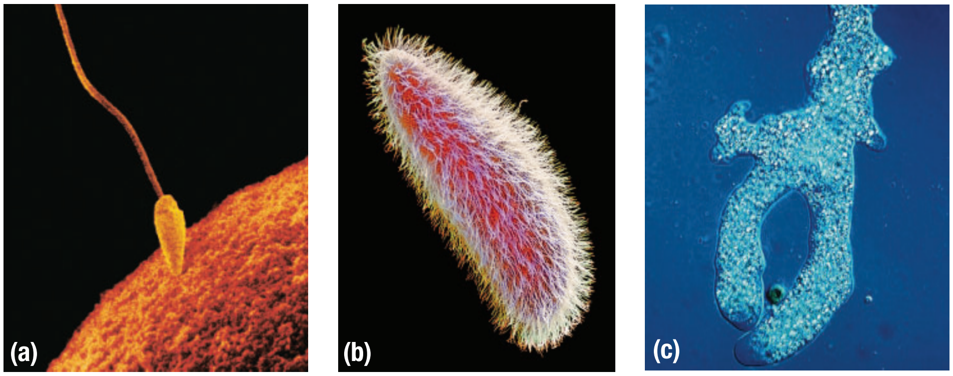


Figure 9 (a) The flagellum of a human sperm, which is about to penetrate an egg; (b) a paramecium with cilia; and (c) a predatory amoeba (*Chaos carolinense*) extending two pseudopods around its hapless meal, a single-celled green alga (*Pandorina*)

The Cell Surface

Like most prokaryotic cells, many types of eukaryotic cells have a **cell wall** around the plasma membrane. Animal cells do not have a cell wall, but plant cells and many protist and fungal cells do. The cell wall is a porous structure that protects, supports, and gives shape to the cell. Water and many solutes easily cross it on the way to and from the plasma membrane.

The cell wall is the outer barrier of a plant cell. It surrounds the plasma membrane and gives structure to the cell, and ultimately the plant (**Figure 10**). The cell wall has a **primary wall** and develops a **secondary wall** during later stages of growth. The primary wall is thin and pliable, which allows the growing plant cell to enlarge. At maturity, the cells in some plant tissues stop enlarging and start secreting a material onto the inner surface of the primary wall. This material forms a firm secondary wall. In addition, some plant cells are covered in an outer waxy cuticle. The cuticle helps to protect exposed surfaces of soft parts of the plant and limits water loss on hot, dry days.

cell wall the outer barrier of a plant cell; the cell wall surrounds the plasma membrane and gives structure to the plant

primary wall a cellulose coating that surrounds a plant cell

secondary wall a coating that is added to a plant cell wall; it is more rigid and often thicker than the primary cell wall

extracellular matrix (ECM) a molecular system that supports and protects a cell; a cell's environment

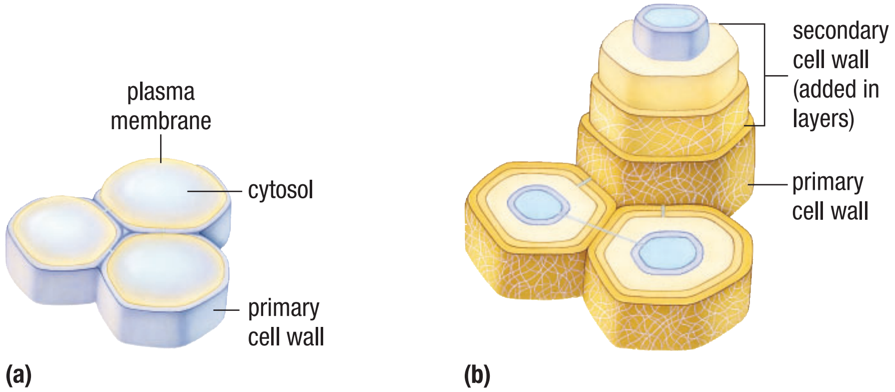


Figure 10 **(a)** Plant cell secretions form the middle layer that cements adjoining cells together. **(b)** In many plant tissues, cells also secrete materials that are deposited in layers on the inner surface of their primary wall. These layers strengthen the wall and maintain its shape.

Most cells of multicellular organisms are surrounded and organized by an **extracellular matrix (ECM)**. This non-living, complex mixture of fibrous proteins and polysaccharides is secreted by cells and varies with the type of tissue. It supports and anchors cells, separates tissues, and functions in cell signalling. The primary cell wall is a type of ECM, which is mostly cellulose in plants. The ECM of fungi is mainly chitin. In most animals, the ECM consists of various kinds of carbohydrates and proteins. The ECM is the basis of tissue organization, and it provides structural support. For example, bone is mostly ECM (**Figure 11**). Bone ECM is mostly collagen, which is a fibrous protein, and it is hardened by mineral deposits. Other protective structures, such as an insect exoskeleton or a bivalve shell, are also examples of ECM.

A cell that is surrounded by a wall or secretions is not isolated. It can still interact with other cells and with its surroundings via **cell junctions**. In multicellular organisms, cell junctions are structures that connect a cell to other cells and to the environment. Cells send and receive ions, molecules, and signals through some junctions. Other junctions help cells recognize and stick to each other and to the ECM.

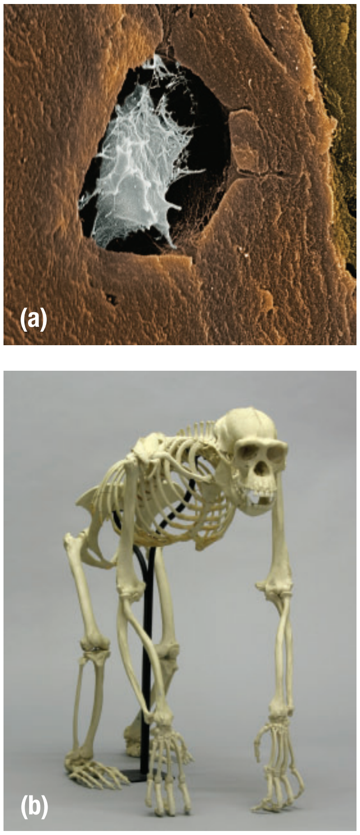


Figure 11 (a) A living cell surrounded by hardened bone tissue, which is the main structural material in the skeleton of most vertebrates (b)

cell junction a structure that allows cells to interact with each other and the surrounding environment

2.1 Review

Summary

- Eukaryotic cells have many different internal components, called organelles. Each organelle has a specific role in cellular activities.
- Plant cells and animal cells have many of the same organelles. Plant cells also have a cell wall, plastids, and a large central vacuole.
- The nucleus isolates and protects most of the cell's DNA.
- The endomembrane system produces lipids, enzymes, and other proteins that are secreted out of the cell or become part of cell membranes.
- Mitochondria produce ATP.
- Eukaryotic cells have an extensive and dynamic framework called a cytoskeleton. The cytoskeleton is used for cell shape, internal structure, movement, and cell division.
- Many cells are surrounded by and supported by a complex extracellular matrix and are able to interact with adjacent cells and the environment via cell junctions.

Questions

1. What is the main difference between eukaryotic cells and prokaryotic cells? Why is this difference significant? K/U
2. Describe the relationship between the following cellular structures and contents. K/U
   (a) endoplasmic reticulum and the nuclear envelope
   (b) the centriole and microtubules
   (c) ribosomes and the nucleolus
   (d) plastids and pigments
3. The nuclear envelope is much more than a simple capsule that contains chromosomes. Describe the structure and function of this dynamic component of a cell. K/U
4. (a) What is the endomembrane system?
   (b) What organelles does it include?
   (c) What does each organelle do? K/U
5. Compare and contrast the structure and the functions of the smooth and rough endoplasmic reticulum. K/U
6. How do lysosomes and peroxisomes differ functionally? K/U
7. Your lab partner is looking at a micrograph of an organelle and is trying to identify it. Your partner tells you that it has a folded membrane that looks like a stack of pancakes. K/U
   (a) What organelle are they observing?
   (b) What is the function of this organelle?
8. Compare and contrast the functions of vesicles and vacuoles. K/U
9. (a) What are mitochondria?
   (b) Describe the structure of mitochondria.
   (c) Why are mitochondria sometimes referred to as the "power plants" of cells? K/U
10. What are the various roles of plastids? How can knowing the colour of a plastid reveal something about its function? K/U
11. Structurally, how are chloroplasts and mitochondria well adapted for energy transfer? Explain your answer for each organelle. K/U
12. What important roles are played by microtubules and microfilaments? K/U
13. Use the Internet and other sources to investigate the functions of the following organelles. What types of cells would you expect to contain them? T/I
    (a) acrosome
    (b) eyespot
    (c) proteasomes
14. Use the Internet and other sources to learn more about red blood cells, which are among the smallest of all human cells. T/I
    (a) How many molecules of hemoglobin does a typical human red blood cell contain?
    (b) The human red blood cell does not have a nucleus. Is this true of the red blood cells in all animals?
    (c) What is the benefit of not having a nucleus?

WEB LINK

Membrane Structure and Functions

2.2

Thanks to a complex system of membrane-bound cells with organelles, we can live healthy lives. When part of this system malfunctions or becomes damaged, however, diseases can result.

Cystic fibrosis (CF) is a genetic disorder that impairs the lungs and gastrointestinal tract. It is caused by mutations to a single gene that codes for a protein called the cystic fibrosis transmembrane conductance regulator, or CFTR. In properly functioning cells, CFTR acts as a membrane transport protein. It helps to move negatively charged chloride ions, Cl^-, out of the cells that line the lungs and intestinal tract and into the surrounding mucus lining (**Figure 1**). This results in an electrical gradient across the membrane and leads to the movement of positively charged sodium ions, Na^+, in the same direction as the chloride. The high Na^+ and Cl^- concentrations cause water, moving by osmosis, to move into the mucus lining.

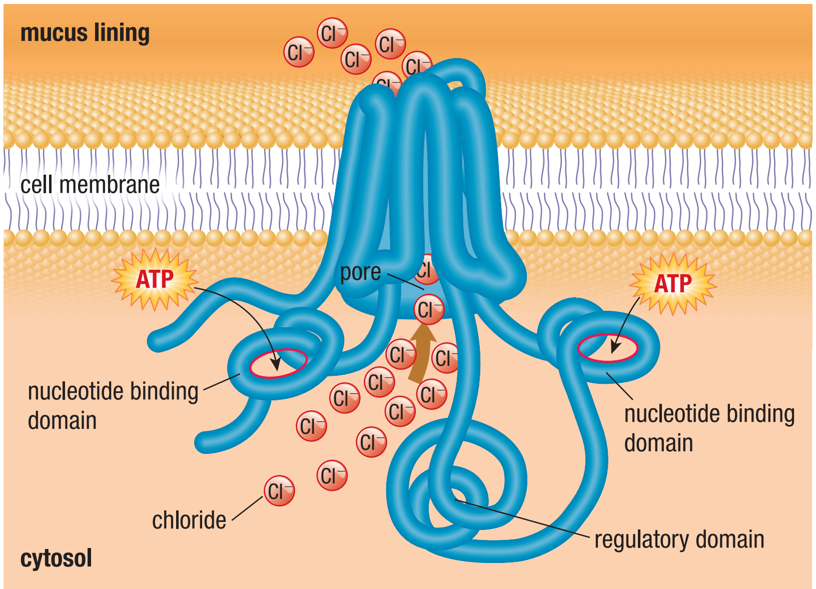


Figure 1 A cystic fibrosis transmembrane conductance regulator (CFTR) is a membrane transport protein that removes chloride from a cell. Cystic fibrosis is caused by a defect in this mechanism.

Keeping the lining of the lungs and intestinal tract hydrated is critical to its proper functioning. In individuals with CF, the Cl^- channel of CFTR malfunctions and water is retained within the cells. A lack of moisture in the mucus lining makes the mucus very thick. When this happens in the lungs, breathing becomes difficult because mucus blocks the airways. The buildup of mucus in the lungs also makes CF patients very susceptible to bacterial infections. In the gastrointestinal system, thick mucus can clog pancreatic ducts, blocking enzymes that would normally enter the small intestine. This can destroy the pancreas and, with it, the ability to produce necessary digestive enzymes. CF patients need to take dietary supplements to survive.

Approximately one in 3900 Canadian children are born with CF. Although the treatment of CF patients is slowly improving, their average lifespan remains under 40 years. Patients may have lung transplants as the disease progresses, but there is no cure. Since CF is caused by a defect to a single gene, the greatest hope is in gene therapy to correct the CFTR gene mutation in the affected cells. However, there are many technical hurdles to overcome before gene therapy becomes a viable treatment option. Understanding the complex structure and function of cell membranes is critical to understanding the causes of diseases such as CF and to finding possible treatments and cures. In this section, you will learn about various membranes and their structures, as well as how they function to protect cells. CAREER LINK WEB LINK

The Fluid Mosaic Model

One of the key factors in the evolution of the cell was the development of the cell membrane. By filtering what went into and out of the cell, the semipermeable plasma membrane allowed for the uptake of key nutrients and the elimination of waste products, while maintaining a protected environment in which metabolic processes could occur. The subsequent development of internal membranes allowed for the compartmentalization of processes. This, in turn, allowed for more complex processes and cell functions. A good example of an internal membrane is the nuclear envelope, which encloses the nucleus and is a characteristic of eukaryotic cells.

fluid mosaic model the idea that a biological membrane consists of a fluid phospholipid bilayer, in which proteins are embedded and float freely

Our current view of membrane structure is based on the **fluid mosaic model** (**Figure 2**). This model proposes that membranes are not rigid, with molecules locked into place. Instead, membranes consist of lipid molecules in which proteins are embedded and float freely. Membranes are described as a fluid because the lipid and protein molecules are generally free to move laterally within the two layers.

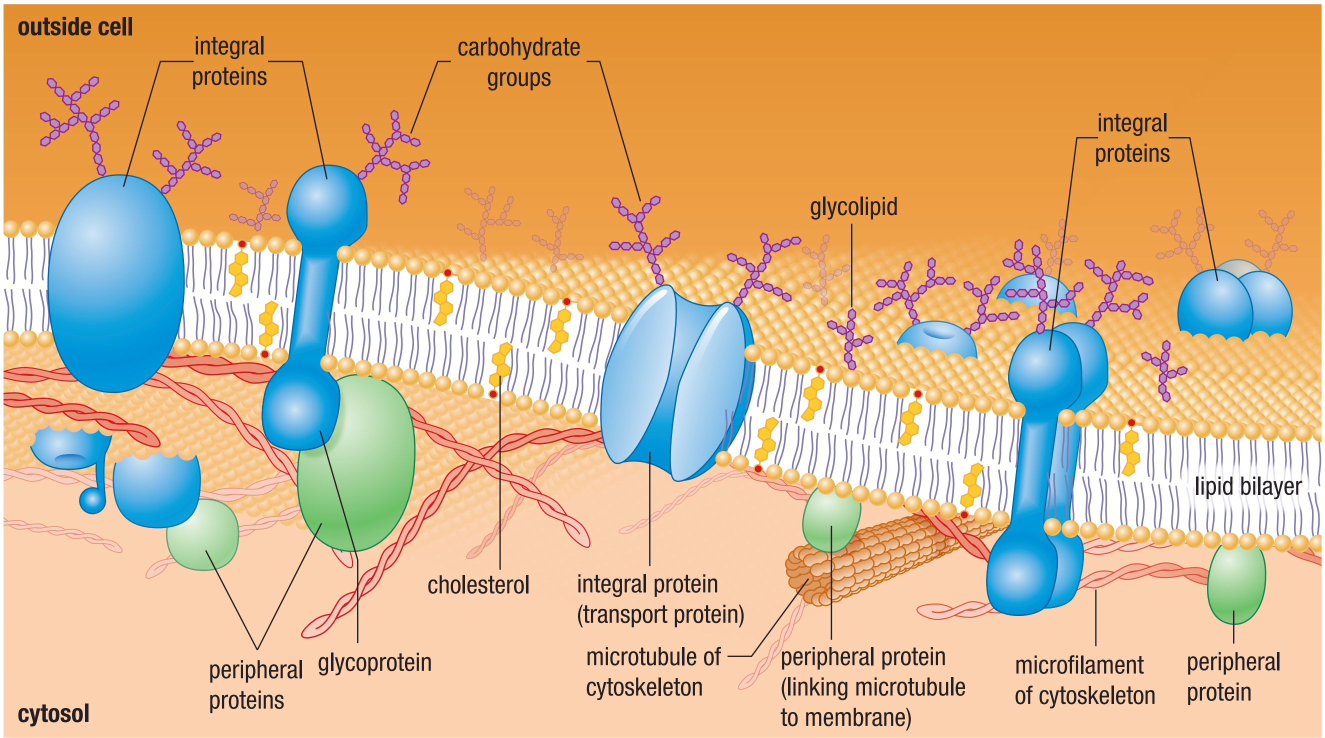


Figure 2 The membrane structure according to the fluid mosaic model, in which integral membrane proteins are suspended individually in a dynamic lipid bilayer

The lipid molecules in all biological membranes are highly dynamic or fluid, which is critical for membrane function. The lipid molecules exist in a double layer, called a bilayer, that is less than 10 nm (nanometres) thick. (By comparison, this page is approximately 100 000 nm thick.) Millions of times a second, the lipid molecules may vibrate, flex back and forth, spin around their long axis, move sideways, and exchange places within the same half of the bilayer.

Membranes contain a mosaic, or wide assortment, of proteins. Some proteins are involved in transport and attachment. Others are enzymes that are used in a variety of biochemical pathways. Because the proteins are larger than the lipid molecules, they move more slowly in the fluid environment of the membrane. A small number of membrane proteins anchor cytoskeleton filaments to the membrane, and thus do not move (Figure 2). Several of the lipid and protein components of some membranes have carbohydrate groups linked to them, forming **glycolipids** and **glycoproteins** that face the exterior of the cell. These molecules often play a role in cell recognition and cell–cell interactions.

glycolipid any membrane lipid that is bound to a carbohydrate

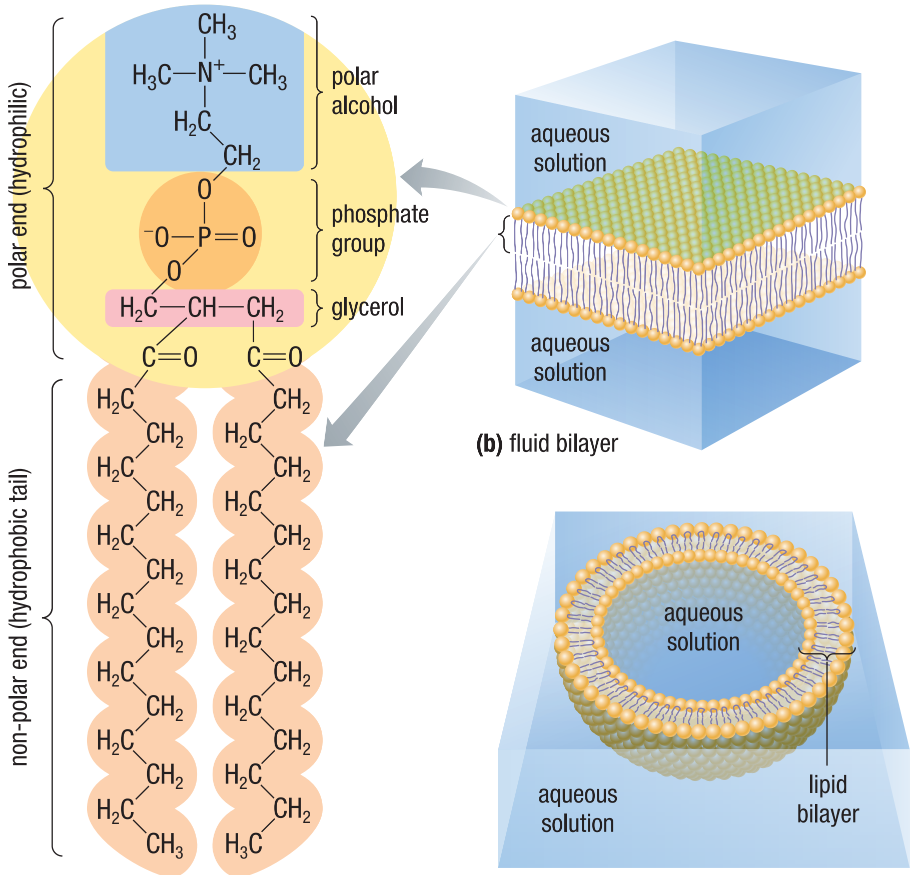
glycoprotein a membrane component that contains a sugar, or carbohydrate, bound to an amino acid

The plasma membrane is the outer cell membrane and is responsible for regulating the substances moving into and out of the cell. Myelin, a membrane that functions to insulate nerve fibres, is composed mostly of lipids (18 % protein and 82 % lipid).

An important characteristic of membranes is membrane asymmetry: the proteins and other components of one half of the lipid bilayer differ from those that make up the other half of the bilayer. This reflects the differences in the functions performed by each half of the membrane. For example, a range of glycolipids and carbohydrate groups attach to proteins on the external half of the membrane, whereas components of the cytoskeleton bind to proteins on the internal half of the membrane. In addition, hormones and growth factors bind to receptor proteins that are found only on the external surface of the plasma membrane. Their binding triggers changes to distinctly different protein components found on the inner surface of the membrane, spurring a cascade of reactions that send a signal within the cell. For example, serotonin is a hormone and neurotransmitter that provides communication between nerve cells. If serotonin is not available in sufficient amounts or does not bind properly, people often experience depression. Doctors treat the symptoms of depression by recommending prescription drugs that help to regulate the level of serotonin.

The Role of Phospholipids

The dominant lipids that are found in membranes are phospholipids. A phospholipid contains two fatty acid tails, which are usually linked to glycerol, a phosphate group, and a compound such as choline (**Figure 3(a)**). This composition is important for membrane function. The fatty acid tails of a phospholipid are very hydrophobic (non-polar), whereas the phosphate-containing head group is charged and hydrophilic (polar). When added to an aqueous solution, large numbers of phospholipids form a bilayer, or a structure that is two lipid molecules thick (**Figure 3(b)** and **(c)**).



(a) phospholipid molecule

(b) fluid bilayer

(c) bilayer vesicle

Figure 3 (a) In a phospholipid molecule (phosphatidyl choline), the head has a polar alcohol (choline, shown in blue), a phosphate group (orange), and a glycerol unit (pink). (b) Individual molecules are free to flex, rotate, and exchange places in a phospholipid bilayer in the fluid state. (c) This phospholipid bilayer is forming a vesicle.

A bilayer forms spontaneously in an aqueous environment because of the tendency of the non-polar hydrophobic fatty acids to aggregate together while the polar heads associate with water. These arrangements are favoured because they represent the lowest energy state, and therefore are more likely than any other arrangement to occur.

Fluidity

The dynamic nature of the lipid bilayer is dependent on how densely the individual lipid molecules can pack together. This is influenced by two major factors: the composition of the lipid molecules that make up the membrane and the temperature. Fatty acids composed of saturated hydrocarbons (in which each carbon is bound to the maximum number of hydrogen atoms) tend to have a straight shape, which allows the lipids to pack together more tightly. In comparison, the double bonds in an unsaturated fatty acid bend its structure, so the lipid molecules are less straight and more loosely packed (Section 1.4).

Membranes remain in a fluid state over a relatively wide range of temperatures. However, if the temperature drops low enough, the lipid molecules in a membrane become closely packed, and the membrane forms a highly viscous semisolid gel. At any given temperature, the fluidity of a membrane is related to the degree to which the membrane lipids are unsaturated. The more unsaturated a membrane is, the lower its gelling temperature.

sterol a type of steroid with an OH group at one end and a non-polar hydrocarbon chain at the other

Besides lipids, a group of compounds called **sterols** also influence membrane fluidity. The best example of a sterol is cholesterol, which is found in the membranes of animal cells, but not in the membranes of plants or prokaryotes (**Figure 4**). Sterols act as membrane stabilizers. At high temperatures, they help to restrain the movement of the lipid molecules in a membrane, thus reducing the fluidity of the membrane. At lower temperatures, however, sterols occupy the spaces between the lipid molecules, thus preventing fatty acids from associating and forming a non-fluid gel.

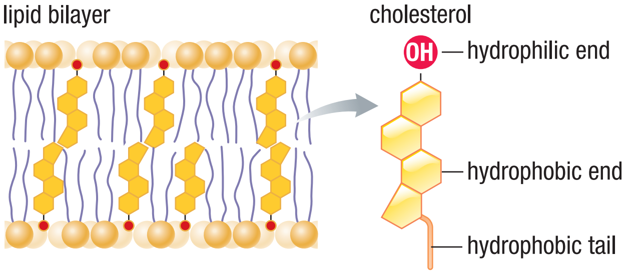


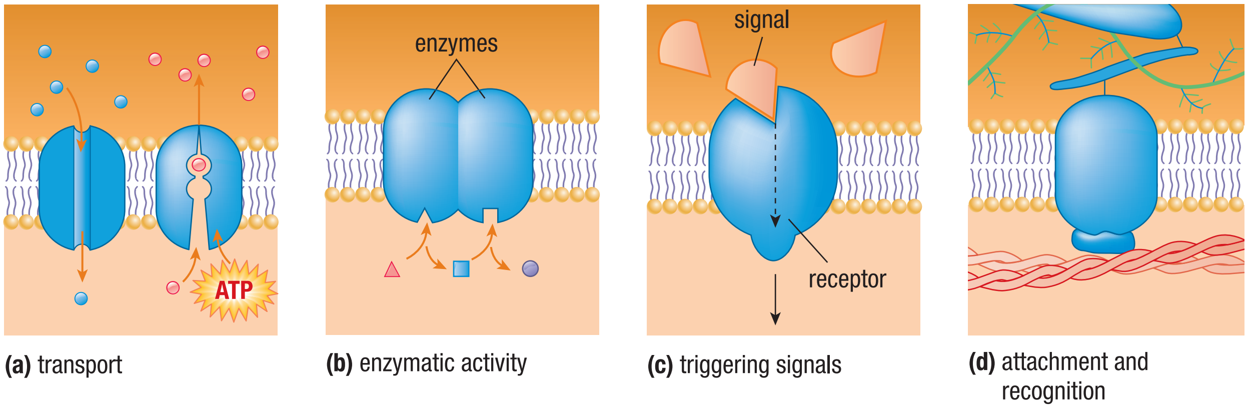
Figure 4 The hydrophilic OH group at one end of the molecule extends into the polar regions of the bilayer. The ring structure extends into the non-polar interior of the membrane.

The Role of Membrane Proteins

Although lipid molecules constitute the backbone of a membrane, the set of proteins associated with the membrane determines its function and makes it unique. Membrane proteins can be separated into the following four functional categories (**Figure 5**, next page):

- *Transport*: Many substances cannot freely diffuse through membranes. Instead, a specific compound may be able to cross a membrane by way of a hydrophilic protein channel. Alternatively, shape shifting may allow some membrane proteins to shuttle molecules from one side of a membrane to the other.
- *Enzymatic activity*: Some membrane proteins, such as those associated with respiration and photosynthesis, are enzymes.
- *Triggering signals*: Membrane proteins may bind to specific chemicals, such as hormones. Binding to these chemicals triggers changes on the inner surface of the membrane, starting a cascade of events within the cell.

- *Attachment and recognition*: Proteins that are exposed to both the internal and external membrane surfaces act as attachment points for a range of cytoskeleton elements, as well as components involved in cell–cell recognition, and bond to the extracellular matrix. For example, surface proteins can recognize elements of disease-causing microbes that may try to invade cells, triggering an immune response.



(a) transport

(b) enzymatic activity

(c) triggering signals

(d) attachment and recognition

Figure 5 The major functions of membrane proteins are (a) transport, (b) enzymatic activity, (c) triggering signals, and (d) attachment and recognition.

All of these functions may exist in a single membrane, and one protein or protein complex may serve more than one of these functions. Beyond function, all membrane proteins can be separated into two additional categories: integral and peripheral membrane proteins (Figure 2). Membrane proteins that are embedded in the lipid bilayer are called **integral membrane proteins**. All integral membrane proteins have at least one region that interacts with the hydrophobic core of the membrane. However, most integral proteins are transmembrane proteins. This means that they span the entire membrane bilayer and have regions that are exposed to the aqueous environment on both sides of the membrane (**Figure 6**).

integral membrane protein a protein that is embedded in the lipid bilayer

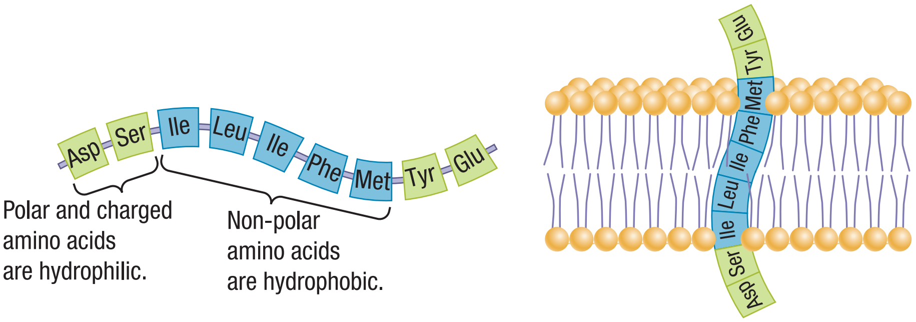

Asp
Ser
Ile
Leu
Ile
Phe
Met
Tyr
Glu
Polar and charged amino acids are hydrophilic.
Non-polar amino acids are hydrophobic.

Figure 6 Transmembrane proteins are easy to identify because they have a segment of non-polar amino acids that are hydrophobic and stay within the membrane, as well as polar hydrophilic regions that are exposed to the environment.

The second major group of proteins are **peripheral membrane proteins**. They are positioned on the surface of a membrane and do not interact with the hydrophobic core of the membrane. Peripheral proteins are held to membrane surfaces by non-covalent bonds (hydrogen bonds and ionic bonds), usually by interacting with the exposed portions of integral proteins as well as directly with membrane lipid molecules. Most peripheral proteins are on the cytosol side of the membrane, and some are part of the cytoskeleton. Examples of peripheral proteins that are part of the cytoskeleton are microtubules, microfilaments, intermediate filaments, and proteins that link the cytoskeleton together. These proteins hold some integral membrane proteins in place.

peripheral membrane protein a protein on the surface of the membrane

2.2 Review

Summary

- A biological membrane consists of a bilayer of phospholipids and proteins that move around freely within the layer. This is described as the fluid mosaic model.
- The fluidity of a plasma membrane depends on the composition of the lipid molecules that make up the membrane, as well as the temperature.
- Membranes contain sterols, which help to maintain their fluidity.
- Membrane proteins have four functions: transport, enzymatic activity, triggering signals, and attachment and recognition of molecules.
- Membrane proteins may be embedded in the lipid bilayer (integral membrane proteins) or positioned on top of the phospholipid bilayer (peripheral membrane proteins).

Questions

1. Our current view of membrane structure is based on the fluid mosaic model. What does the word "mosaic" refer to in the expression "fluid mosaic model"? K/U
2. When referring to membrane glycolipids and glycoproteins, what does the prefix "glyco" indicate? K/U
3. When comparing the outside and inside halves of a cell membrane's phospholipid bilayer, the composition of lipids on the two surfaces is asymmetrical. K/U
    (a) Describe how membranes are asymmetric.
    (b) Why is membrane asymmetry an important characteristic in cell membranes?
4. How does the structure of the plasma membrane facilitate its function? K/U
5. (a) What is meant by membrane fluidity?
    (b) Explain how the chemical makeup of a membrane gives it fluidity.
    (c) Which components affect the fluidity of a membrane?
    (d) How is their movement related to this fluidity? K/U T/I
6. (a) What is the function of sterols?
    (b) Identify a sterol that is found in membranes of animal cells but not in plants or prokaryotes. K/U
7. Cholesterol molecules are aligned with the lipid molecules on both sides of the bilayer. Is cholesterol polar or non-polar? Explain your answer. K/U
8. The basic components of a cell membrane are phospholipids, proteins, and carbohydrates. What are the functions of each component? K/U
9. Explain the four functional categories of membrane proteins. K/U
10. How are protein receptors and enzymes similar? K/U
11. If proteins were rigid, how would this affect their ability to act as receptors? K/U
12. Describe what is meant by integral and peripheral membrane proteins. How do they differ in their chemical makeup and their arrangement of amino acids? K/U
13. Do all organelles have identical membranes? Give some examples of similarities and differences. K/U
14. Serotonin is a hormone and neurotransmitter that provides communication between nerve cells. If it is not available in sufficient amounts or does not bind properly, people can experience depression. Using the Internet and other sources, find out how SSRIs (selective serotonin reuptake inhibitors), a newer class of antidepressants often prescribed by doctors to alleviate depression, work. T/I

WEB LINK

2.3 Explore Applications of Cell Biology

Nanotechnology in Medicine

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

The biggest breakthroughs in medicine may soon come in the smallest packages. Nanotechnology—the study and use of material at the nanoscale level—will soon be used in a hospital near you. A nanometre (nm) is one billionth of a metre. To put this in perspective, a human hair is about 10 000 nm wide, and a sheet of paper is about 100 000 nm thick.

Scientists are researching ways to use nano-sized robots, or nanobots, in areas such as cancer research, cell and bone repair, gene therapy, and drug delivery (**Figure 1**). Tiny nanobots could one day zoom through the body and report on the health of the tissues, an impending bacterial infection, or the possibility of cancer forming in the body. The possibilities are seemingly endless. CAREER LINK

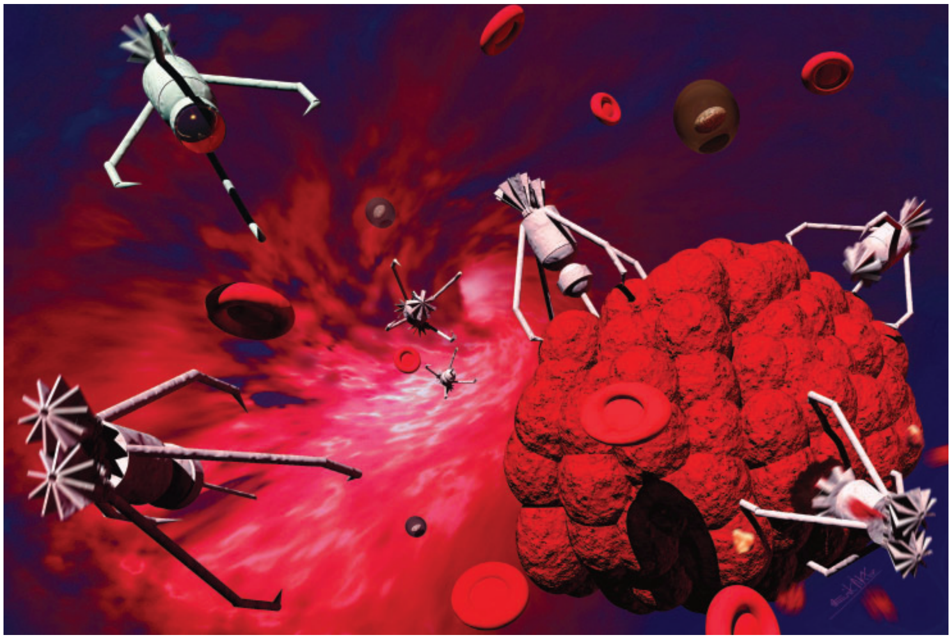


Figure 1 An artist's rendition of nanobots attacking a cancer cell

One of the main challenges, at this stage in the development of nanobots, is predicting how something this small will react once it is in the body. For example, there is currently no way to know if nanomaterials will be taken up by non-target cells, which could cause toxicity in patients. Some research has shown that nanobots are stable in animal cells, and the hope is that soon they will be tested in humans.

In the meantime, nanotechnology is currently widely used in electronics research, manufacturing, and material science. These applications will improve our understanding of how to apply nanotechnology in all fields of medicine.

The Application

As a scientific researcher, you are assigned to write an article for a science magazine, create a documentary or website, or make an audio presentation about the current status of nanotechnology in medicine. You will provide an overview of nanotechnology applications related to human health care and give some examples of current breakthroughs.

Your Goal

To research the current status of the application of nanotechnology in medicine and to determine its potential for future use

Research

SKILLS HANDBOOK A4.1, A4.2

Use the Internet and other resources to research how nanotechnology is currently being used in medicine. WEB LINK

- Identify which, if any, nanotechnology applications are now being used, which are likely to be used in the near future, and which are still "futuristic"
- How do or might scientists use nanobots to study or treat heart disease or cancer? How might nanobots be used to fight the common cold?
- What are the advantages of using nanotechnology?
- What are the drawbacks or risks? What possible harm could nanobots have on human and environmental health?
- What types of applications would you like to see nanotechnology applied to in the future?

Summarize

Summarize your findings by selecting the most relevant and important information and examples you gathered in your research. Consolidate these into a format that you can use for preparing your presentation.

Communicate

Consider the following questions when preparing your report or presentation:

- What is the main purpose of your report or presentation?
- What examples will you use to help you support your opinions?
- Did you include opposing viewpoints on controversial issues, if they exist?
- How will you end your report or presentation?
- Did you include any "looking to the future" examples?

Communicate your findings in your chosen medium: as a magazine article, web page, or audio or video documentary. If time permits, share you report or presentation with your class, and have a class discussion about the future of nanotechnology.

Plan for **Action**

What nanotechnology research is being conducted in Ontario or in Canada? How would you get involved in nanotechnology applications? Choose one of the following roles, and then conduct online research to find out how you might go about preparing for this role:

- researcher in nanotechnology at a university
- worker at a nanotechnology company
- educator in the risks of nanotechnology

WEB LINK

Transport across Membranes

2.4

For a cell to survive and function, it must take in nutrients, expel waste, and communicate with its environment and neighbouring cells. This exchanging of substances is a complex process because the plasma membrane must be highly selective. It must be able to take in very large food molecules while preventing very small and valuable molecules from leaving the cell. It must also be able to recognize foreign substances that are harmful and block their passage while, at the same time, expelling the cell's toxic waste products. To further complicate matters, some molecules cannot be stopped by the plasma membrane—they enter and exit regardless of whether or not it is desirable for the cell. When this happens, the cell must be able to withstand the consequences.

The transmembrane exchange of materials is not limited to the outer surface of the cell. Countless substances must be able to cross the organelle membranes within a eukaryotic cell. In the mitochondria and chloroplasts, chemical reactions take place within the internal fluids, separated from the cytosol by two or three membrane layers. For these reactions to occur, reactants must be able to enter the organelle, while products must be permitted to leave. In this section, you will explore the free movement of certain molecules, such as O_2 and CO_2, across membranes, as well as the specialized cell transport mechanisms that are used to control the entry and exit of other molecules.

Passive Membrane Transport

Passive transport is the movement of a substance across a membrane without the need to expend chemical energy. Diffusion drives passive transport. Diffusion is the net movement of a substance from a region of higher concentration to a region of lower concentration. It occurs because molecules are in constant motion and, in an ideal closed environment, tend to become uniformly distributed in space. Diffusion is the primary mechanism of solute movement within a cell and between cellular compartments separated by a membrane. If molecules are more concentrated in one region of a solution or on one side of a membrane, the random motion of the molecules causes them to become evenly distributed (**Figure 1**). As diffusion proceeds, there is a net movement of molecules in one direction until the concentrations on both sides of the membrane become equal.

passive transport the movement of a substance across a membrane without expending energy

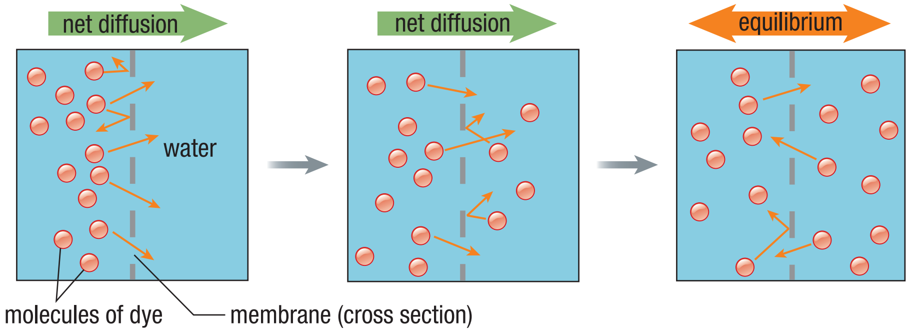


Figure 1 Diffusion is the process in which molecules move from a region of higher concentration to a region of lower concentration.

The rate of diffusion depends on the concentration difference, or concentration gradient, that exists between two areas or across a membrane. The larger the gradient, the faster the rate of diffusion is. Even after the concentration of molecules or ions is the same in both regions, the molecules or ions continue to move from one region to another. However, there is no net change in concentration. This is an example of a **dynamic equilibrium**.

dynamic equilibrium the state in which continuous action results in balanced conditions

Membranes have selective permeability, which means that some molecules can diffuse very rapidly across a membrane while other molecules are unable to transit the membrane without assistance. Two major factors, size and charge, determine the ease with which a molecule or ion can move across a membrane. There are two types of passive transport: simple diffusion and facilitated diffusion.

Simple Diffusion

simple diffusion the ability of small and non-polar substances to move across a membrane unassisted

Simple diffusion is the ability of substances to move across a membrane unassisted (**Figure 2**). Very small non-polar molecules, such as O_2 and CO_2, are readily soluble in the hydrophobic interior of a membrane and move rapidly from one side to the other. Non-polar steroid hormones and non-polar drugs can also cross a membrane easily. Small uncharged molecules, such as water and glycerol, even though they are polar, are still able to move quite rapidly across a membrane. In contrast, most membranes are practically impermeable to large molecules and ions. Compared with the rate of transport of water, the movement of small ions is about one-billionth the speed.

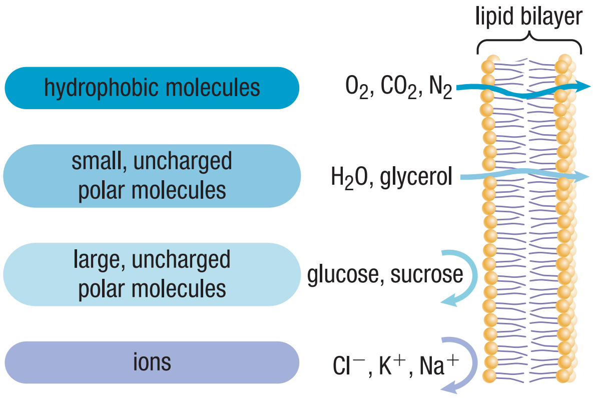


Figure 2 The size and charge of a molecule affect the rate of diffusion across a membrane.

Facilitated Diffusion

facilitated diffusion the facilitated transport of ions and polar molecules through a membrane via protein complexes

transport protein an integral membrane protein that provides a pathway for molecules to cross a membrane

channel protein a hydrophilic pathway in a membrane that enables water and ions to pass through

A slow rate of diffusion may not keep up with the demand that metabolic processes often have for ions and many polar and charged molecules, such as water, amino acids, and sugars. Diffusion of these compounds across a membrane can be helped or facilitated by protein complexes that span the membrane. This is known as **facilitated diffusion**. Although facilitated diffusion involves specific transporters, the movement of the molecules and ions is still driven by diffusion based on a concentration gradient across the membrane. When equilibrium is reached and there is no longer a concentration gradient, facilitated diffusion stops.

Facilitated diffusion is carried out by integral membrane proteins called **transport proteins** that extend throughout the membrane. There are two types of transport proteins: channel proteins and carrier proteins. **Channel proteins** form hydrophilic pathways in the membrane through which water and certain ions can pass (**Figure 3**).

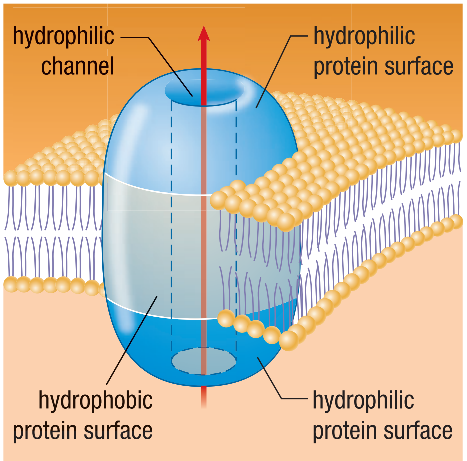

hydrophilic channel
hydrophilic protein surface
hydrophobic protein surface
hydrophilic protein surface

Figure 3 Channel proteins

Other channel proteins facilitate the transport of ions such as Na^+, K^+, Ca^{2+}, and Cl^-. Most of these ion channels, which occur in all eukaryotes, are voltage-gated channels. This means that they switch between open, closed, and intermediate states. The gates are opened or closed by changes in voltage across the membrane or by binding signal molecules. In animals, voltage-gated ion channels are used for nerve conduction and for the control of muscle contractions. In some people, however, the channel proteins do not function properly. People with a muscle ion channel disease often experience muscle stiffness or weakness as a result.

carrier protein a protein that binds to a molecule and transports it across the lipid bilayer

Carrier proteins also form passageways through the lipid bilayer (**Figure 4**). Each carrier protein binds to a specific solute, such as a glucose molecule or a particular amino acid, and transports it across the lipid bilayer. Diffusion is the driving mechanism for moving a solute down its concentration gradient, but it would not be able to move through the membrane without carrier proteins. When performing the transport step, the carrier protein changes shape, allowing the solute to move from one side of the membrane to the other. This change in shape distinguishes how carrier proteins and channel proteins function.

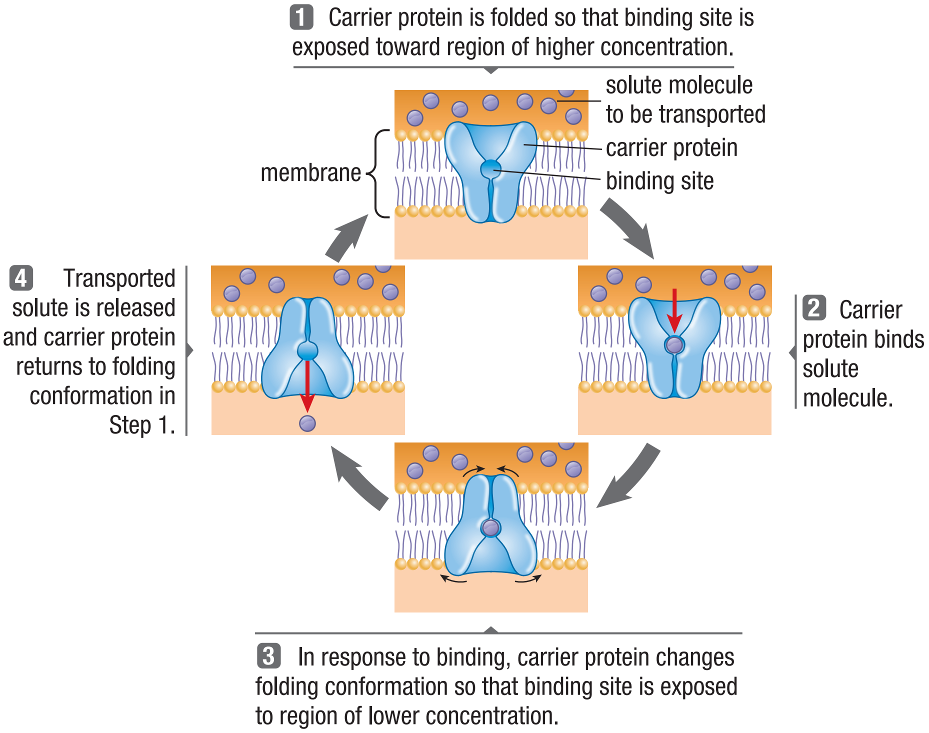

1 Carrier protein is folded so that binding site is exposed toward region of higher concentration.
solute molecule to be transported
carrier protein
binding site
membrane
2 Carrier protein binds solute molecule.
3 In response to binding, carrier protein changes folding conformation so that binding site is exposed to region of lower concentration.
4 Transported solute is released and carrier protein returns to folding conformation in Step 1.

Figure 4 Carrier proteins transport solutes across membranes.

Many transport proteins are very selective about which solutes they will carry. For example, transporters that carry glucose are unable to transport fructose, which is structurally very similar. This specificity allows for tight control over what gets in and out of cells and cellular compartments. The types of transport proteins that are present in the plasma membrane and on the outer membrane of mitochondria depend ultimately on the type of cell and growth conditions.

In facilitated diffusion, the rate of diffusion across the membrane is influenced not only by the concentration gradient and the efficiency of the transport protein but also by the number of transport molecules. **Figure 5** illustrates the influence of solute concentration on the rate of diffusion in both facilitated and simple diffusion.

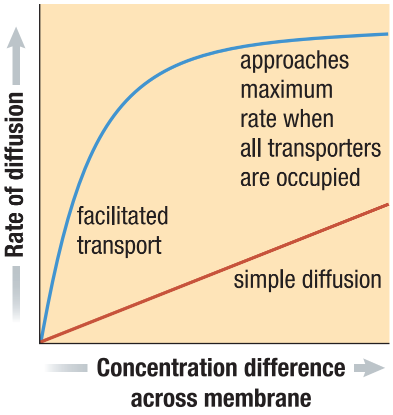


Figure 5 The rate of diffusion across a membrane increases as the difference in concentration increases. In facilitated transport, the maximum rate is reached quickly but is limited by the number of available transport proteins in the membrane.

Osmosis

osmosis the passive diffusion of water across a membrane

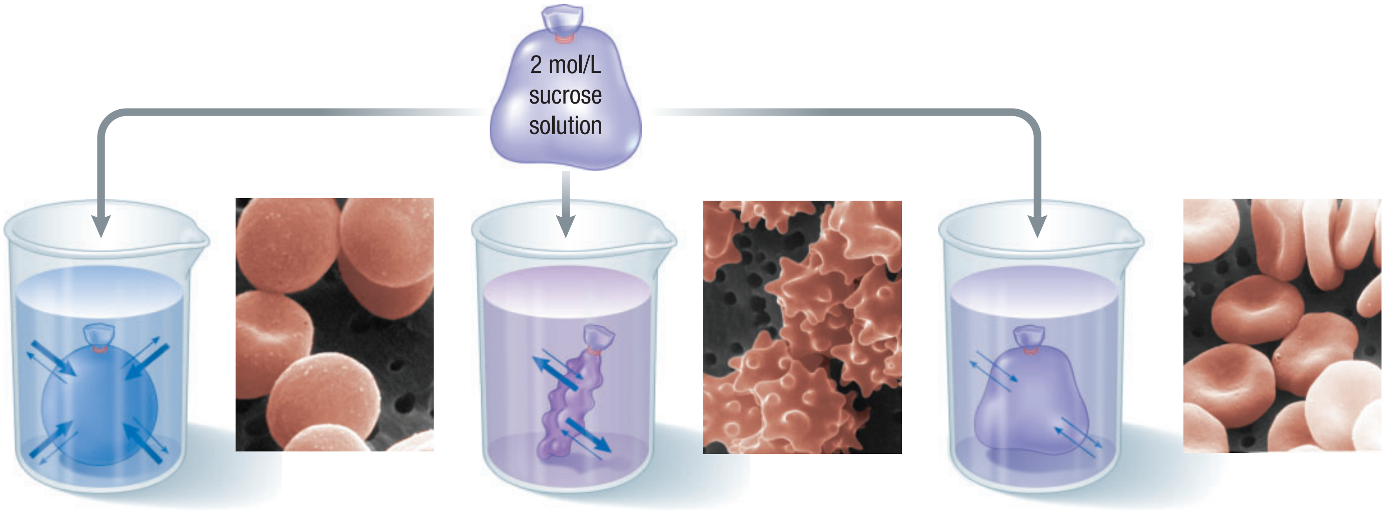
Like solutes, water can diffuse passively across a membrane. The diffusion of water across a membrane is such a fundamental process in biology that it is given a special name: **osmosis**. In living cells, the inward or outward movement of water by osmosis develops forces that can cause cells to swell or shrink. Water always diffuses from an area of lower solute concentration (high water concentration) to an area of greater solute concentration (low water concentration) and is therefore influenced by any difference or change in solute concentration on either side of a membrane.

If the solution that is surrounding a cell contains dissolved substances at lower concentrations than they are in the cell, the solution is said to be **hypotonic** to the cell. When a cell is in a hypotonic solution, water enters by osmosis and the cell tends to swell (**Figure 6(a)**). Animal cells in a hypotonic solution may actually swell to the point of bursting. In contrast, an organism in a solution that contains salts or other molecules at higher concentrations than they are in its body must expend energy to replace the water that is lost by osmosis. In this situation, the outside solution is said to be **hypertonic** to the organism's cells (**Figure 6(b)**). The concentration of water inside and outside cells is often equal or **isotonic**, as shown in **Figure 6(c)**.

hypotonic the property of a solution that has a lower solute concentration than another solution

hypertonic the property of a solution that has a higher solute concentration than another solution

isotonic the property of a solution that has the same solute concentration as another solution



(a) hypotonic conditions:
The distilled water is hypotonic to the solution in the bag; net movement of water is into the bag; cells swell.

(b) hypertonic conditions:
The 10 mol/L solution is hypertonic to the solution in the bag; net movement of water is out of the bag; cells shrink.

(c) isotonic conditions:
The solutions inside and outside the bag are isotonic; there is no net movement of water into or out of the bag; no change in cell size or shape.

Figure 6 A cellophane bag filled with a 2 mol/L sucrose solution is placed in (a) a hypotonic solution, (b) a hypertonic solution, and (c) an isotonic solution. The cellophane is permeable to water but not to sucrose molecules. The width of the arrows shows the amount of water movement. The animal cell micrographs show the corresponding effects on red blood cells placed in hypotonic, hypertonic, and isotonic solutions.

Mini **Investigation**

Observing Diffusion and Osmosis

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A1, A2.1**

In this investigation, you will use dialysis tubing to test for the diffusion of substances across a semipermeable membrane. You will use Lugol's iodine to test for the presence of starch. Lugol's solution turns blue or black when starch is present.

Equipment and Materials: safety goggles; lab apron; 250 mL beaker; 25 mL pipette with pipette filler; scissors; electronic balance; 15 cm length of dialysis tubing (soaked in warm water); 2 pieces of cotton string; tap water; glucose test strip; 15 mL of 15 % glucose/1 % starch solution; paper towels; Lugol's iodine solution in a dropper bottle

Iodine in Lugol's solution is an irritant. If it touches your skin, wash your skin immediately with soap and water, and inform the teacher.

1. Put on your safety goggles and lab apron.
2. Gently take the dialysis tubing from the water. Use the string to tie off one end.
3. Fill your beaker with 150 mL of water. Test the water for glucose using the test strip. Record your results.

4. Fill the dialysis tubing with water to see if the tubing leaks. If not, empty the water and fill the tubing with 15 mL of glucose/starch solution using a pipette and pipette filler.
5. Use the glucose test strip to test the solution in the tubing. Record your results. Then tie off the open end of the tubing with the string (**Figure 7**).

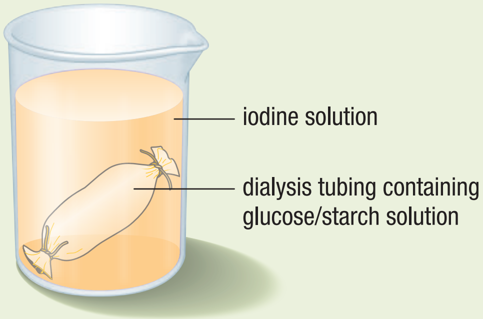

iodine solution
dialysis tubing containing glucose/starch solution

Figure 7

6. Rinse the tubing thoroughly, cut off any extra string, and gently dry the outside surface with a paper towel. Determine and record the mass of the tubing with the solution. Observe and record how full the tubing is.
7. Place the closed tubing in the beaker. Add water if necessary, so the tubing is completely submerged.
8. Add several drops of Lugol's iodine to the water in the beaker until the water turns pale orange.
9. Let the beaker stand for 30 min.
10. Test the water in the beaker for glucose. Record your results.
11. Remove the dialysis tubing, and observe its contents. Record your observations.
12. Gently dry the outside surface of the tubing. Determine and record the mass of the tubing with the solution.

A. Did the water in the beaker initially contain glucose? Did it contain glucose after 30 min with the tubing immersed? T/I

B. Did the solution in the tubing change colour? Is the colour different from the colour of the contents of the beaker? Explain. T/I

C. Was there a change in mass or an obvious change in volume of the solution in the tubing? Account for your observations. T/I

D. Draw a labelled diagram to explain the roles of diffusion and osmosis in this investigation. T/I C

Active Membrane Transport

You have learned how passive transport, driven by a concentration gradient, accounts for much of the movement of water, ions, and many types of molecules into and out of cells. Often, however, some substances must be moved against a concentration gradient, from a region of lower concentration to a region of higher concentration. Many of these substances are carried across a membrane against their concentration gradient by an energy-dependent process called **active transport**. Using "pumps," active transport is able to concentrate specific compounds inside cells and push others out. For example, in muscle cells, the calcium ion concentration in one compartment can be as much as 30 000 times as great as the calcium ion concentration in another compartment. Such a huge concentration difference, which is necessary for normal muscle function, is established and maintained through active transport.

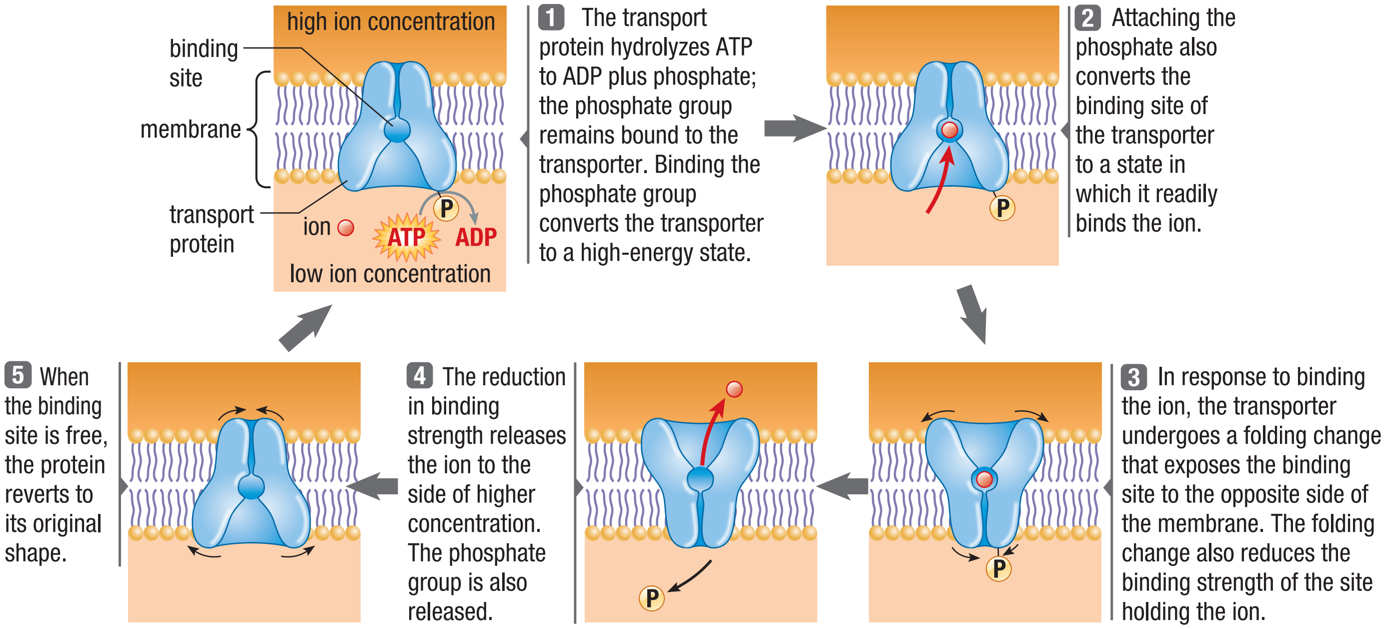
active transport the movement of substances across membranes against their concentration gradient using pumps

Here, the term "active" refers to the fact that the cell has to expend energy, which is usually in the form of ATP, to pump molecules across a membrane. Scientists estimate that about 25 % of a cell's energy requirements are for active transport.

Primary Active Transport

All primary active transport pumps move positively charged ions, such as H^+, Ca^{2+}, Na^+, and K^+, across membranes. The concentration gradients that are established by these active transport pumps underlie functions that are absolutely essential for cellular life. For example, an H^+ pump (also called a proton pump) in the plasma membrane pushes hydrogen ions from the cytosol to the cell exterior. This pump temporarily binds to a phosphate group removed from ATP during the pumping cycle (**Figure 8**, next page). A Ca^{2+} pump (or calcium pump) pumps Ca^{2+} from the cytosol to the cell exterior and into the vesicles of the endoplasmic reticulum (ER). A Na^+/K^+ pump (or sodium–potassium pump) located in the plasma membrane simultaneously pushes three Na^+ ions out of the cell and two K^+ ions into the cell.

Voltage (an electrical potential difference) across the plasma or internal membrane is a difference in electrical charge on either side of the membrane. This difference results from an unequal net distribution of the many positive cations and negative anions. Differences in the various ion concentrations are the result of both



1 The transport protein hydrolyzes ATP to ADP plus phosphate; the phosphate group remains bound to the transporter. Binding the phosphate group converts the transporter to a high-energy state.

2 Attaching the phosphate also converts the binding site of the transporter to a state in which it readily binds the ion.

3 In response to binding the ion, the transporter undergoes a folding change that exposes the binding site to the opposite side of the membrane. The folding change also reduces the binding strength of the site holding the ion.

4 The reduction in binding strength releases the ion to the side of higher concentration. The phosphate group is also released.

5 When the binding site is free, the protein reverts to its original shape.

Figure 8 This model shows how an active transport pump operates.

passive and active transport, as well as chemical reactions that take place on both sides of the membrane. The combined effects of the voltage and the differences in ion concentrations create an **electrochemical gradient**. An electrochemical gradient is a form of stored potential energy that can be used for other transport mechanisms. For example, the electrochemical gradient across the plasma membrane is involved in the movement of ions associated with nerve impulse transmission.

electrochemical gradient the combined effects of a difference in electrical potential energy and a difference in the concentration gradients of ions

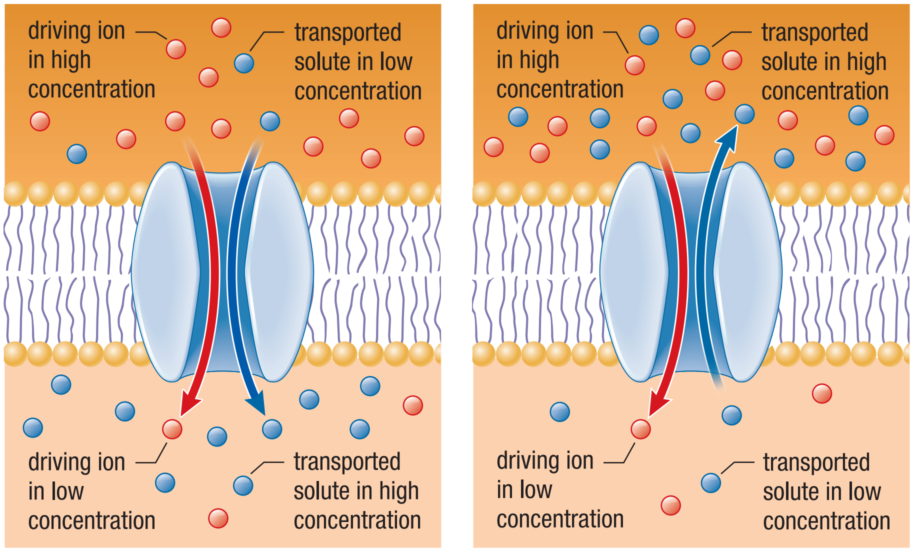
Secondary Active Transport

A secondary active transport pump uses the concentration gradient of an ion, established by a primary pump, as its energy source. For example, the driving force for most secondary active transport in animal cells is the high outside/low inside Na^+ gradient set up by the sodium–potassium pump. Secondary active transport is facilitated by two mechanisms, known as symport and antiport (**Figure 9**).

Investigation **2.4.1**

Plasma Membrane Permeability (p. 98)

You have learned about diffusion and osmosis. You have also learned about the importance of plasma membranes to proper cell and organelle function. This investigation will give you an opportunity to examine outside factors that can affect cells.


driving ion in high concentration
transported solute in low concentration
driving ion in low concentration
transported solute in high concentration
driving ion in high concentration
transported solute in high concentration
driving ion in low concentration
transported solute in low concentration

(a) symport **(b)** antiport

Figure 9 (a) In symport, the transported solute moves in the same direction as the gradient of the driving ion. (b) In antiport, the transported solute moves in the direction that is opposite to the gradient of the driving ion.

In symport, a solute moves through the membrane channel in the same direction as the driving ion. In antiport, the driving ion moves through the membrane channel in one direction, providing the energy for the active transport of another molecule in the opposite direction. In many cases, ions such as Na^+ are exchanged by antiport.

Comparison of Passive and Active Transport

Both passive transport and active transport move ions and small molecules across cellular membranes. **Table 1** summarizes the characteristics of these two transport mechanisms.

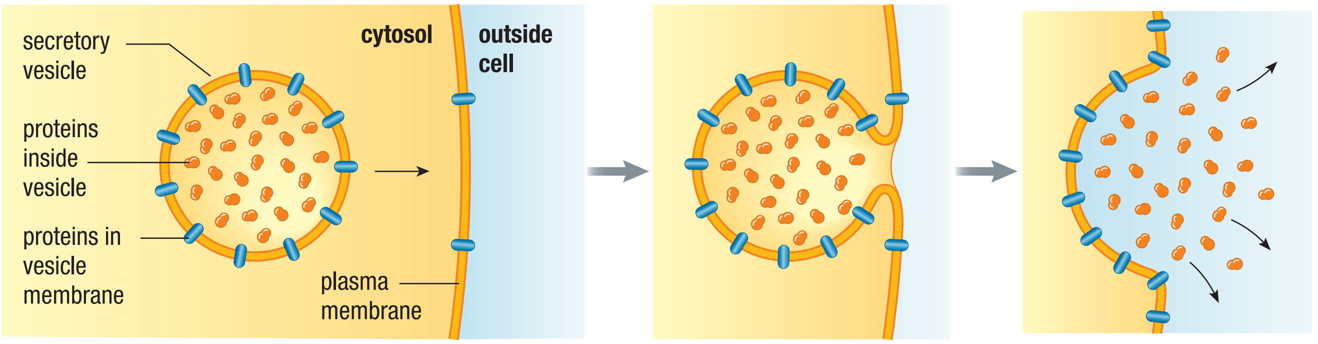
Table 1 Characteristics of Transport Mechanisms

	Passive transport		
Characteristic	**Simple diffusion**	**Facilitated diffusion**	**Active transport**
Membrane component that is responsible for influencing transport	lipids	proteins	proteins
Binding to transported substance	no	yes	yes
Energy source	concentration gradients	concentration gradients	ATP hydrolysis or concentration gradients
Direction of transport	with gradient of transported substance	with gradient of transported substance	against gradient of transported substance
Specificity for molecules or molecular classes	non-specific	specific	specific
Saturation at high concentrations of transported molecules	no	yes	yes

Exocytosis and Endocytosis

The largest molecules that can be transported across a cellular membrane by passive or active transport are about the size of amino acids or monosaccharides such as glucose. However, eukaryotic cells can export and import larger molecules by two other mechanisms, called exocytosis and endocytosis. The export of materials by exocytosis primarily carries secretory proteins and some waste materials from the cytosol to the exterior of a cell. Import by endocytosis may carry proteins, larger aggregates of molecules, or even whole cells from the exterior of a cell into the cytosol. Exocytosis and endocytosis also contribute to the back-and-forth flow of portions of actual membranes between the endomembrane system and the plasma membrane. Both exocytosis and endocytosis require energy. Thus, both processes stop if the ability of a cell to make ATP is inhibited.

In exocytosis, secretory vesicles move through the cytosol and contact the plasma membrane (**Figure 10**). The vesicle membrane fuses with the plasma membrane, releasing the contents of the vesicle to the exterior of the cell. All eukaryotic cells



1 The secretory vesicle approaches the plasma membrane.

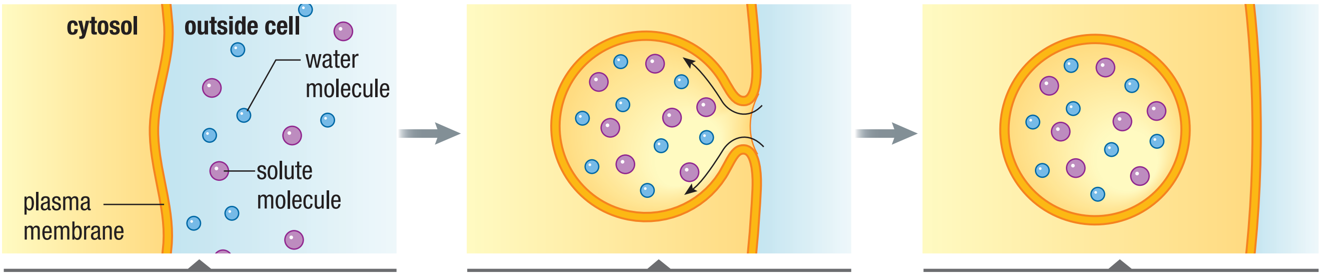
2 The vesicle fuses with the plasma membrane.

3 Proteins inside the vesicle are released to the cell exterior; proteins in the vesicle membrane become part of the plasma membrane.

Figure 10 Exocytosis

secrete materials outside the cell through exocytosis. For example, glandular cells in animals secrete peptide hormones or milk proteins, and cells lining the digestive tract secrete mucus and digestive enzymes. Plant cells secrete carbohydrates by exocytosis to build a strong cell wall.

In endocytosis, proteins and other substances are trapped in a pit-like depression that bulges inward from the plasma membrane. The depression then pinches off as an endocytic vesicle. Endocytosis takes place in most eukaryotic cells by one of three distinct but related pathways. In the simplest of these pathways, bulk-phase endocytosis (sometimes called pinocytosis, meaning "cell drinking"), extracellular water is taken in, along with any molecules that happen to be in solution in the water (**Figure 11**). No binding by surface receptors takes place.



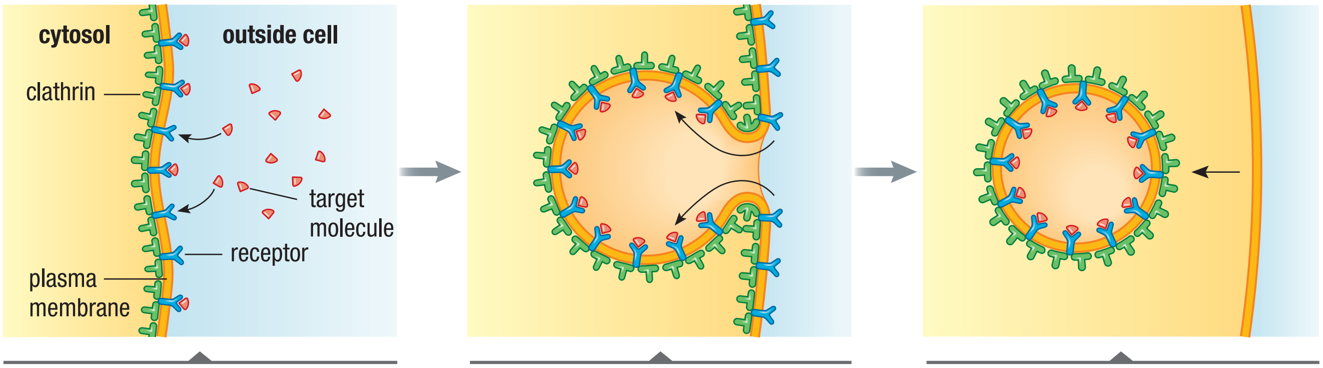
1 Solute molecules and water molecules are outside the plasma membrane.

2 The membrane folds inward, enclosing solute and water molecules.

3 The pocket pinches off as an endocytic vesicle.

Figure 11 Bulk-phase endocytosis, or pinocytosis

In the second endocytic pathway, receptor-mediated endocytosis, the molecules to be taken in are bound to the outer cell surface by receptor proteins (**Figure 12**). The receptors bind to only certain molecules—primarily proteins or molecules carried by proteins. After binding, the receptors collect into a pit coated with a network of proteins, called clathrin, that reinforce the cytosol side. The coated pit then breaks free of the membrane to form a vesicle. In the cytosol, the vesicle loses its clathrin coating and may fuse with a lysosome. Enzymes within the lysosome then digest the cargo, breaking it down into smaller molecules that are useful to the cell.



1 Substances attach to membrane receptors.

2 The membrane folds inward.

3 The pocket pinches off as an endocytic vesicle.

Figure 12 Receptor-mediated endocytosis

A third type of endocytosis is phagocytosis. It is the pathway in which cells engulf bacteria, parts of dead cells, viruses, or other foreign particles. This pathway is most commonly performed by a macrophage, a type of white blood cell that helps to fight infection by engulfing invading organisms or particles.

Through the combined mechanisms of passive transport, active transport, exocytosis, and endocytosis, cells maintain their internal concentrations of ions and molecules and exchange larger molecules, such as proteins, with their surroundings.

2.4 Review

Summary

- Cells and cell organelles must interact with their environment by allowing and controlling the inward and outward movement of molecules and ions through their membrane.
- Some molecules can pass through a membrane using passive transport (simple or facilitated diffusion), which depends on a concentration gradient.
- Osmosis is the passive diffusion of water across a membrane.
- Active transport moves a substance against a concentration gradient across a membrane, using a pump. Primary active transport pumps include H^+, Ca^+, Na^+, and K^+ pumps. Secondary transport pumps occur via symport or antiport.
- Endocytosis moves aggregate molecules into the cell. Exocytosis moves proteins and wastes out of the cell.

Questions

1. Your biology study partner asks you a question about the concentration gradient of water. K/U
   (a) What is meant by the term "concentration gradient"?
   (b) Is your study partner using the term correctly in reference to water? Explain why or why not.
2. Facilitated diffusion is specific. What does this mean? K/U
3. A red blood cell was placed in a beaker of solution. The cell immediately began to swell and finally burst. Explain what happened, referring to the cytosol of the cell and the solution in the beaker. K/U
4. Distilled water is considered hypotonic to body cells. Explain. T/I
5. Compare the energy requirements of passive transport, primary active transport, and secondary active transport. K/U
6. (a) How do size, polarity, and charge influence the ability of a substance to diffuse across a membrane?
   (b) Which combinations of these factors require cells to use active transport to move a substance across a membrane? K/U
7. (a) How does the concentration of a solute on the two sides of a membrane affect passive transport?
   (b) How does this concentration affect primary and secondary active transport? T/I
8. (a) What process is shown in the micrographs in **Figure 13**?
   (b) Draw a labelled scientific drawing of the micrographs. T/I C

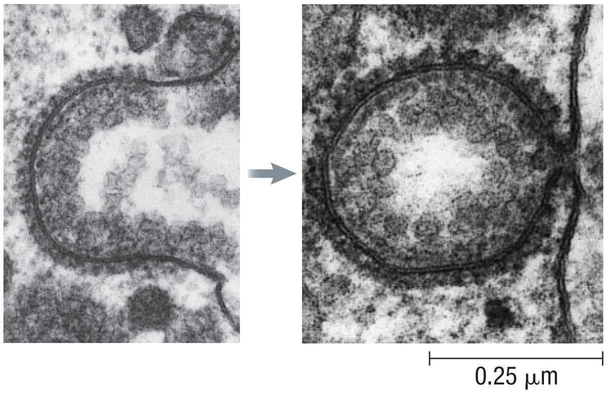


Figure 13

9. The transport of molecules across cellular membranes is important for the proper functioning of cells. Explain the role of transport across cell membranes in the proper functioning of the following:
   (a) red blood cells
   (b) cells in the gut
   (c) the release of hormones K/U T/I
10. Cystic fibrosis can be caused by the Cl^- transport channel malfunctioning. Conduct research to identify a disease that can be caused by a K^+ or Na^+ transport channel malfunctioning. What are the physical effects of this disease? CAREER LINK T/I A

WEB LINK

Investigation 2.4.1 CONTROLLED EXPERIMENT

Plasma Membrane Permeability

You may have noticed that when a beetroot is cooked in water, the water becomes red (**Figure 1**). The red colour is created by betacyanin compounds that are found in cell vacuoles. Beets also contain nitrate, which is used in the production of ATP. In this investigation, you will examine the effects of temperature and solvents, such as detergents and alcohol, on the release of pigments from beetroot cells.

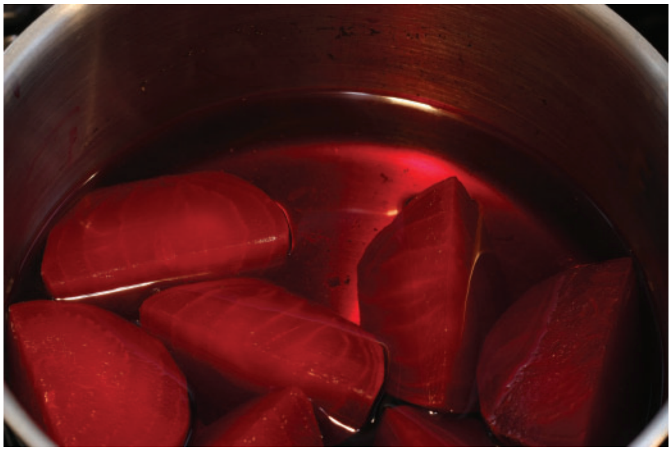


Figure 1 Cooking a beetroot causes the cooking water to turn red.

Testable Questions

Part A: Will temperature influence the release of pigment from beetroot cells?
Part B: How do organic solvents and/or detergents influence plasma membranes?

Predictions

Part A: Predict what will happen to beetroot pigment when a beetroot core is heated in water.
Part B: Predict what will happen to beetroot pigment when a beetroot core is placed in a detergent or solvent solution.

Variables

Read the Procedure to determine the dependent and independent variables in this experiment. How would you classify water temperature? What about the amount of detergent? What will be your controls?

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- **Predicting**
- Planning
- **Controlling Variables**
- **Performing**
- **Observing**
- **Analyzing**
- Evaluating
- Communicating

Experimental Design

SKILLS HANDBOOK A2.2

You will use prepared raw beetroot cores to investigate how temperature and solvents affect the integrity of the plasma membranes. You will use the release of beetroot pigment and the final colour of the surrounding solution to judge the effects on the plasma membranes.

Equipment and Materials

- protective gloves
- 4 beakers (400 mL)
- 4 thermometers
- 2 hot plates
- 8–12 test tubes (18 mm × 150 mm) with stoppers
- wax pencil (for labelling test tubes)
- measuring cylinder
- test-tube holder
- test-tube rack
- forceps
- 8–12 raw beetroot cores (0.5 cm × 0.5 cm × 3.0 cm) soaked in distilled water for 24 h
- tap water for water baths
- ice
- dish detergent or another detergent
- 70 % isopropyl alcohol
- paper towels

Alcohol is flammable. Turn off all open flames in the room.

Procedure

Part A: Temperature Experiment

1. While wearing protective gloves, obtain four beetroot cores that have been soaked in distilled water for 24 h.
2. Use the four beakers, four thermometers, two hot plates, water, and ice to set up a series of water baths at the following temperatures: near 0 °C, room temperature, near 50 °C, and over 80 °C.
3. Label each test tube with the temperature of one water bath and your initials.

4. Put one beetroot core into each test tube. Add 5 mL of distilled water.
5. Use the test-tube holder to place each test tube in the corresponding water bath.
6. Use the thermometers to monitor the temperatures of the water baths, and adjust the water baths as necessary.
7. After the test tubes have been in the water baths for 30 min, use the test-tube holder to transfer the three test tubes that are not in the room-temperature water bath to the room-temperature water bath. This will allow the contents to return to room temperature quickly.
8. After all test tubes have been in the room-temperature water bath for 5 min, place them in a test-tube rack.
9. Place a stopper in each test tube, and gently swirl the contents. Then use forceps to remove and dispose of the beetroot cores.
10. Compare the depth of the colour of the solution in each test tube. Rank the solutions from least concentrated to most concentrated. Record your observations in a table.

Part B: Detergent or Solvent Experiment

The following steps can be used for either the detergent or organic solvent tests.

11. Obtain four more beetroot cores that have been soaked in distilled water for 24 h.
12. Label four test tubes with your initials and the names of the three detergent solutions (0.1 %, 1 %, 10 %) OR the three alcohol solutions (5 %, 25 %, 50 %). Label the fourth test tube "control: distilled water."
13. Put one beetroot core in each test tube. Add 5 mL of the appropriate solution to each test tube.
14. After 30 min, repeat Steps 9 and 10 from Part A.
15. If instructed to do so by your teacher, repeat Part B with a second set of test solutions (detergent or alcohol).

Analyze and Evaluate

(a) Describe the influence of temperature on the release of pigments from the beetroot cells. T/I

(b) Describe the effects of a solvent and/or detergent on the release of pigments from the beetroot cells. T/I

(c) How did your results compare with your classmates' results? T/I

(d) Account for the influence of temperature on the amount of pigment released. Do you think the temperature affected the movement of the pigment particles, the membrane permeability, or both? Explain your reasoning. T/I

(e) Account for the influence of the detergent and/or solvent on the amount of pigment released. Do you think the detergent and/or solvent affected the movement of the pigment particles, the membrane permeability, or both? Explain your reasoning. T/I

Apply and Extend

(f) Investigate the structure and function of the red betacyanin pigments. What types of plants contain them? Do these pigments have any health benefits? CAREER LINK T/I A

(g) How might changes in temperature be expected to influence cellular activity? T/I

(h) In this investigation, you used a simple subjective ranking of colour intensity. How could you change this investigation to gather and analyze quantitative data? T/I

WEB LINK

CHAPTER 2 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 70. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 70. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

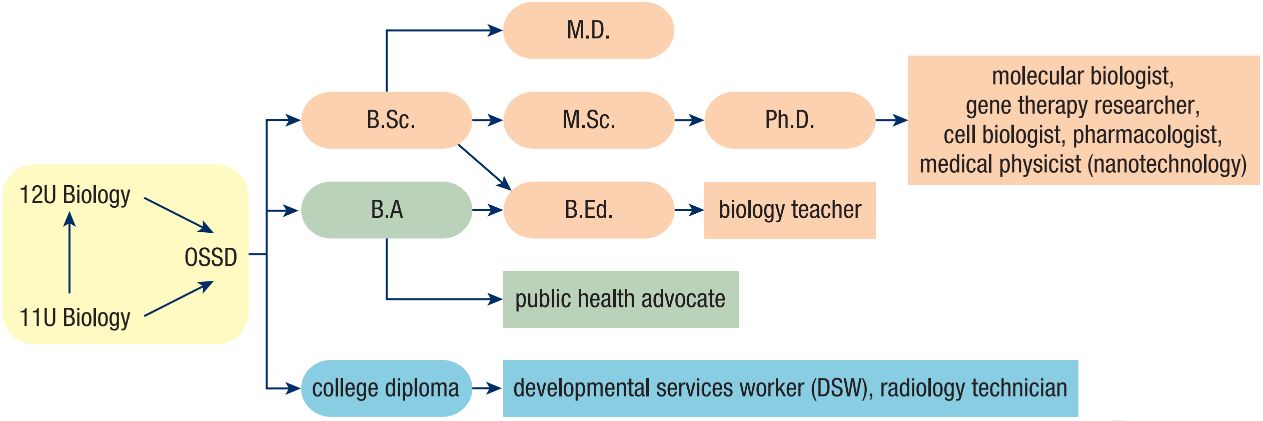
organelle (p. 72)
plasma membrane (p. 72)
nuclear envelope (p. 73)
endomembrane system (p. 74)
endoplasmic reticulum (ER) (p. 75)
rough ER (p. 75)
smooth ER (p. 75)
vesicle (p. 75)
vacuole (p. 75)
lysosome (p. 76)
Golgi body (p. 76)
mitochondrion (p. 76)
plastid (p. 77)
chloroplast (p. 77)
chromoplast (p. 77)
amyloplast (p. 77)
cytoskeleton (p. 77)
microfilament (p. 78)
flagellum (p. 78)
cilia (p. 78)
cell wall (p. 79)
primary wall (p. 79)
secondary wall (p. 79)
extracellular matrix (ECM) (p. 79)
cell junction (p. 79)
fluid mosaic model (p. 82)
glycolipid (p. 82)
glycoprotein (p. 82)
sterol (p. 84)
integral membrane protein (p. 85)
peripheral membrane protein (p. 85)
passive transport (p. 89)
dynamic equilibrium (p. 89)
simple diffusion (p. 90)
facilitated diffusion (p. 90)
transport protein (p. 90)
channel protein (p. 90)
carrier protein (p. 91)
osmosis (p. 91)
hypotonic (p. 92)
hypertonic (p. 92)
isotonic (p. 92)
active transport (p. 93)
electrochemical gradient (p. 94)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to cellular biology that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.



M.D.
B.Sc.
M.Sc.
Ph.D.
molecular biologist, gene therapy researcher, cell biologist, pharmacologist, medical physicist (nanotechnology)
12U Biology
11U Biology
OSSD
B.A
B.Ed.
biology teacher
public health advocate
college diploma
developmental services worker (DSW), radiology technician

CAREER LINK

CHAPTER 2 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What is a key difference between eukaryotes and prokaryotes? (2.1) K/U
   (a) Eukaryotes do not have a nuclear membrane.
   (b) Prokaryotes do not have a nuclear membrane.
   (c) Eukaryotes do not have cell walls.
   (d) Prokaryotes do not have cell walls.
2. Which term refers to the series of interacting organelles between the nucleus and the plasma membrane? (2.1) K/U
   (a) endomembrane system
   (b) nuclear envelope
   (c) intermembranal system
   (d) total functioning unit of the cell
3. Which type of cells have mitochondria? (2.1) K/U
   (a) eukaryotes
   (b) prokaryotes
   (c) cells that perform photosynthesis
   (d) all cells
4. Which of the following is NOT a function carried out by a plastid? (2.1) K/U
   (a) energy production in animal cells
   (b) energy production in leaves
   (c) synthesis and storage of protein molecules
   (d) synthesis and storage of sugar molecules
5. Which of the following symptoms may be typical of cystic fibrosis? (2.2) K/U
   (a) back pain
   (b) bacterial infections in the lungs
   (c) weak muscles and bones
   (d) headaches and dizziness
6. How thick is a lipid bilayer? (2.2) K/U
   (a) 0.01 nm
   (b) 10 nm
   (c) 1000 nm
   (d) 1 000 000 nm
7. What materials make up a cell membrane? (2.2) K/U
   (a) lipids, nucleic acids, and proteins
   (b) lipids, cholesterol, and proteins
   (c) lipids, nucleic acids, and cholesterol
   (d) cholesterol, nucleic acids, and proteins
8. Which form of energy is needed for passive transport to occur? (2.4) K/U
   (a) ATP
   (b) glucose energy
   (c) ionization energy
   (d) no energy is required
9. In which direction do proton pumps move hydrogen ions? (2.4) K/U
   (a) from the cytosol to the outside of the cell
   (b) from the cytosol into the nucleus of the cell
   (c) from the nucleus into the cytosol of the cell
   (d) from the outside of the cell into the cytosol

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Nucleoplasm is analogous to cytosol. (2.1) K/U
11. Subunits of ribosomes are assembled from proteins and DNA in the cytosol. (2.1) K/U
12. Cells that specialize in making and storing enzymes need less rough ER than average. (2.1) K/U
13. Mitochondria and chloroplasts have evolved from cells that were engulfed by other cells. (2.1) K/U
14. The fluid mosaic model describes how membranes consist of lipid molecules with embedded proteins. (2.2) K/U
15. Nanotechnology may turn out to be a dangerous medicinal method because nanorobots may be too small to be accurately monitored and controlled. (2.3) K/U
16. All primary active transport pumps move negatively charged ions across membranes. (2.4) K/U
17. If a semipermeable bag that contains a 2 mol/L sucrose solution is placed in a 10 mol/L sucrose solution, it will shrink. (2.4) T/I
18. Secondary active transport pumps use the concentration gradient of an ion, which has been established by a primary pump, as their energy source. (2.4) K/U
19. Endocytosis moves proteins and wastes out of the cell. (2.4) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 2 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which of the following best describes the nuclear envelope? (2.1) K/U
   - (a) protein coat
   - (b) doubled-up lipid bilayer
   - (c) single lipid layer
   - (d) the same as the plasma membrane
2. Which of the following best describes a nuclear pore? (2.1) K/U
   - (a) hole through the centriole
   - (b) temporary opening for selective transport
   - (c) passive transport channel
   - (d) cluster of proteins that selectively transport only some materials
3. Which of the following is a function of vesicles? (2.1) K/U
   - (a) processing water
   - (b) disposing of waste
   - (c) producing toxins
   - (d) isolating carbohydrates
4. In eukaryotes, which organelle is responsible for making ATP? (2.1) K/U
   - (a) nucleus
   - (b) Golgi body
   - (c) mitochondrion
   - (d) membrane
5. Which type of cells do mitochondria resemble? (2.1) K/U
   - (a) neurons
   - (b) muscle cells
   - (c) bacteria
   - (d) cork cells
6. In cystic fibrosis, the CFTR protein malfunctions. What is the result? (2.2) K/U
   - (a) Water is purged from cells.
   - (b) Sodium is purged from cells.
   - (c) Chloride is purged from cells.
   - (d) Water is retained inside cells.
7. How are peripheral proteins attached to the cytosol side of the cell membrane? (2.2) K/U
   - (a) by covalent bonds
   - (b) by non-covalent bonds
   - (c) by adhesion
   - (d) by glycosidic bonds
8. Which of the following is a function of the cytoskeleton? (2.2) T/I
   - (a) transports materials outside the cell
   - (b) provides energy for the cell
   - (c) aids in cell movement
   - (d) stores materials for the cell
9. Which part(s) of a phospholipid is (are) hydrophilic? (2.2) T/I
   - (a) the entire phospholipid molecule
   - (b) the phosphate group and the glycerol head
   - (c) the fatty acid tails
   - (d) the phosphate group only
10. What would make a hypertonic solution isotonic? (2.4) T/I
    - (a) remove water
    - (b) add water
    - (c) remove solutes and water
    - (d) add solutes
11. Which of the following best describes the movement of molecules from an area of high concentration to an area of low concentration? (2.4) T/I
    - (a) osmosis
    - (b) diffusion
    - (c) passive transport
    - (d) active transport
12. Which of the following best describes phagocytosis? (2.4) T/I
    - (a) a type of endocytosis that takes in large particles
    - (b) a type of endocytosis that takes in fluids
    - (c) a type of exocytosis that removes large particles
    - (d) a type of exocytosis that removes wastes and fluids
13. Which statement best describes the rate of O_2 movement across a cell membrane? (2.4) T/I
    - (a) It is slow because the O_2 molecule needs time to go through the respiration reactions.
    - (b) It is fast because the O_2 molecule needs to go through the respiration reactions.
    - (c) It is slow because O_2 is a large polar molecule.
    - (d) It is fast because O_2 is a small non-polar molecule.

14. How does the rate of facilitated transport compare with the rate of simple diffusion for the same substance? (2.4) K/U
   (a) Simple diffusion is always the faster method.
   (b) The rates are approximately equal.
   (c) Facilitated transport is faster if there are enough transporters.
   (d) The rates depend on the type of cell, so there is not enough information to compare the rates.

15. Why does a cell swell when it is placed in a hypotonic solution? (2.4) K/U
   (a) Water diffuses to an area where there is more water.
   (b) Water diffuses to an area where the solute concentration is lower.
   (c) Water diffuses to an area where the solute concentration is higher.
   (d) The solution must be outside the human body.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

16. Mitochondria do not have their own DNA. (2.1) K/U
17. Plants and animals have similar plastids. (2.1) K/U
18. Mitochondria and chloroplasts probably evolved in a similar way. (2.1) T/I
19. Microfilaments help amoebas feed. (2.1) K/U
20. The purpose of the cuticle is to give structure to a plant. (2.1) K/U
21. A cell with a double membrane filled with membrane-bound organelles is a prokaryotic cell. (2.1) K/U
22. While plant and animal cells have many of the same organelles, only plant cells have a cell wall, plastids, and a large central vacuole. (2.1) K/U
23. Membranes contain steroids that help to maintain their fluidity. (2.2) K/U
24. Integral membrane proteins are positioned on top of the lipid layer. (2.2) K/U
25. The evolution of more external membranes allowed for more complex processes to develop within cells. (2.2) T/I
26. Voltage-gated channels remain open during the rest phase. (2.4) K/U
27. Osmosis is defined as the diffusion of water across a membrane. (2.4) K/U
28. Simple and facilitated diffusion both depend on a concentration gradient. (2.4) K/U
29. Secondary active transport pumps depend on the concentration gradient of an ion established by a primary pump as its source of energy. (2.4) K/U
30. Binding by surface receptors takes place in bulk-phase endocytosis. (2.4) K/U
31. Most materials that are ingested by endocytosis do not change in form once they enter the cell. (2.4) K/U

Match each term on the left with the most appropriate description on the right.

32. (a) cytoskeleton
   (b) mitochondrion
   (c) lysosome
   (d) smooth ER
   (e) rough ER
   (f) peroxisome
   (g) vesicle
   (h) Golgi body

   (i) synthesizes and modifies proteins
   (ii) transports and stores cellular materials
   (iii) produces energy for the cell
   (iv) makes lipids and breaks down fats and carbohydrates
   (v) sorts and ships proteins and lipids
   (vi) digests and recycles cellular materials
   (vii) inactivates toxins
   (viii) moves the cell and its components (2.1) T/I

33. (a) plasma membrane
   (b) myelin
   (c) integral membrane proteins
   (d) peripheral membrane proteins

   (i) are generally found on the cytosol side of the membrane, while some are part of the cytoskeleton
   (ii) span the entire membrane bilayer and have regions that are exposed to the aqueous environment
   (iii) is responsible for regulating the substances moving in and out of the cell
   (iv) is composed of 18 % protein and 82 % lipids (2.2) K/U

Write a short answer to each question.

34. How do cells with walls interact with each other? (2.1) K/U
35. Describe two functions of the nucleus. (2.1) K/U
36. List some of the functions and products of Golgi bodies. (2.1) K/U
37. Describe the stroma of a plastid. (2.1) K/U
38. Name and describe the structure and functions of the two types of endoplasmic reticulum. (2.1) K/U C
39. Explain the role of chloroplasts and chromoplasts as a tomato ripens. (2.1) T/I
40. (a) Which organelles have a membrane?
   (b) Which two organelles are most likely to pinch off vesicles that contain proteins? (2.1) K/U

41. Explain three typical tasks of different microfilaments. Give specific examples, with locations and names. (2.1) K/U

42. Use **Figure 1** to draw a cross-section of a nucleus. Label all the components. (2.1) K/U C

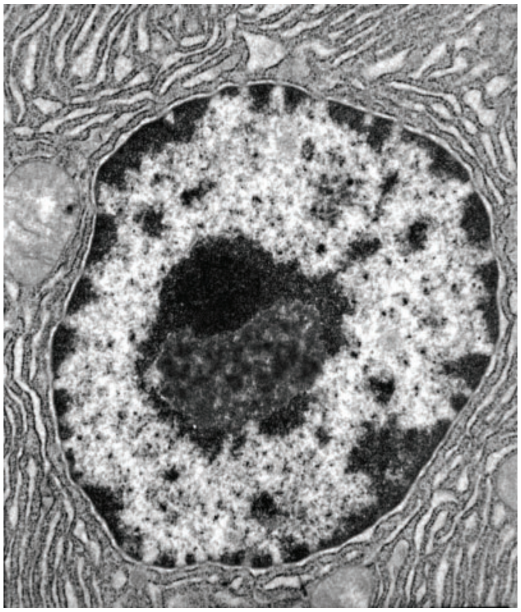


Figure 1

43. (a) Identify the organelle that is shown in **Figure 2**.
    (b) In what type of organism is it found?
    (c) What are the dark areas in the centre made from: proteins, fluid, membrane, or nucleic acids? (2.1) K/U

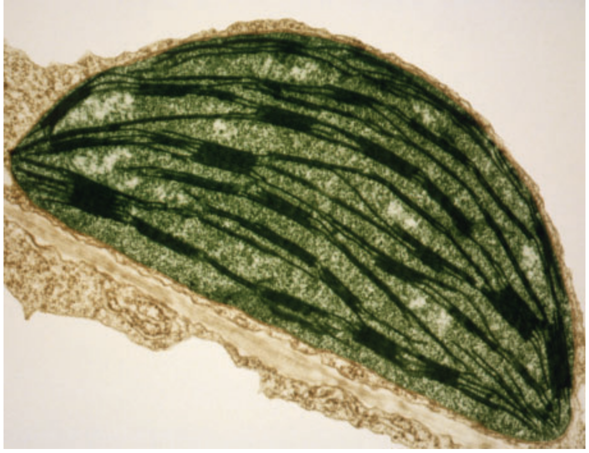


Figure 2

44. How does an organized array of microtubules benefit a sperm cell? (2.1) K/U

45. Sketch and label the cell wall of a plant cell, showing how the cells are packed together. Also show how cells can add layers of secondary cell wall inside the original cell wall. (2.1) K/U C

46. Use a table to compare plant parts with lignin deposits to younger plant parts without lignin. (2.1) K/U

47. Plant cell walls are a type of extracellular matrix that is made mostly of cellulose. Describe the extracellular matrix in fungi and animal bone. (2.1) K/U

48. List and describe the four functions of membrane proteins. (2.2) K/U

49. **Figure 3** shows a lipid bilayer. Name the structures that are indicated with letters. (2.2) K/U

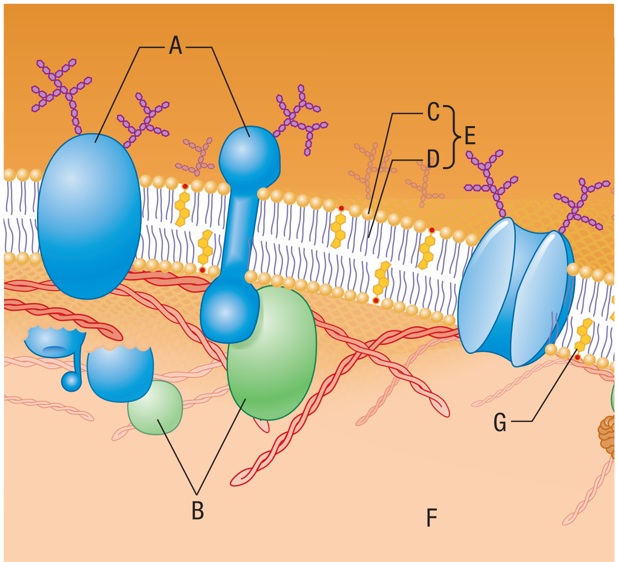


Figure 3

50. Explain why proteins move more slowly than lipid molecules within a plasma membrane. (2.2) K/U

51. List four examples of biological applications of nano-sized robots that are currently being researched. (2.3) K/U

52. Which molecules require facilitated diffusion? Explain why. (2.4) K/U

53. Describe the movement of molecules during diffusion, and explain how this applies to diffusion through the cell membrane. (2.4) K/U

54. (a) List the three ways that cells obtain nutrients, as well as the types of nutrients that cells obtain each way.
    (b) List the two ways that particles exit the cell. (2.4) K/U

55. Create a Venn diagram to compare active transport with passive transport. Compare four features. Discuss each feature in terms of the molecules or ions involved and the conditions required. (2.4) K/U C

Understanding

56. Vesicles can fuse with other organelles, or they can form by pinching off from other organelles. Describe examples of these two processes. (2.1) K/U

57. Compare and contrast the nuclear envelope with the plasma membrane. What do you think is the key difference? (2.1) K/U T/I

58. Explain why some cells, such as some pancreas cells, that make a greater quantity of enzymes need more rough ER than other cells. (2.1) K/U T/I

59. (a) What is an amyloplast?
    (b) Would you be more likely to find amyloplasts in the leaves or the tubers of a potato (**Figure 4**)? Explain why. (2.1) K/U

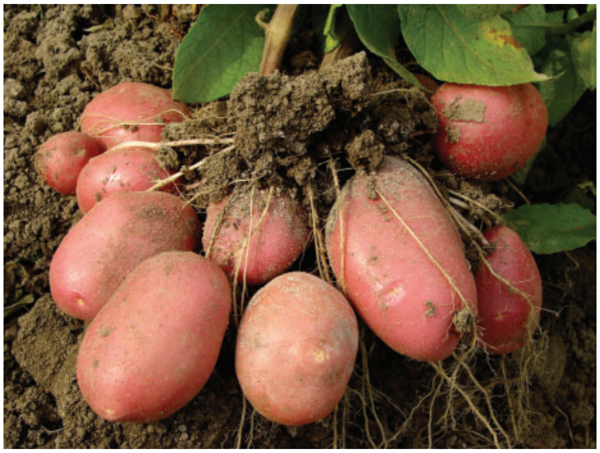


Figure 4

60. Membranes are essential for the transport of an enzyme after it is created in a pancreatic cell by a ribosome on the rough ER. Explain why. (2.1) K/U

61. What organelles do you suspect might play a particularly important role in each activity? (2.1) K/U T/I
    (a) running
    (b) sweating
    (c) growing hair
    (d) replacing and repairing cells
    (e) passing on information to offspring
    (f) digesting dinner

62. Explain why the plasma membrane is described as both a fluid and a mosaic. (2.2) K/U

63. Compare the peripheral and integral membrane proteins that are associated with the bilayer membrane of the cell. Use a sketch to illustrate your answer. (2.2) K/U C

64. Use a Venn diagram to compare chloroplasts and mitochondria. (2.2) T/I C

65. What physical factors might limit the maximum efficiency of cell membranes to perform their functions? (2.2) T/I

66. **Figure 5** shows diffusion across a permeable membrane. (2.4) T/I A
    (a) Does movement across the membrane stop in any of these situations? Explain.
    (b) What will be the net direction of solute flow in Figure 5(a)? How long will this situation last?

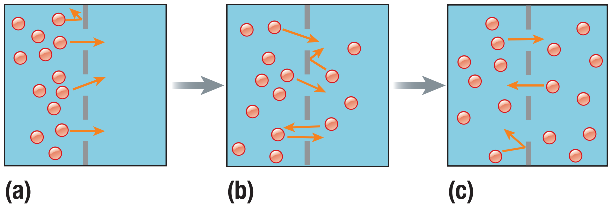


Figure 5

67. (a) Use a concept map or another graphic organizer to describe how the size and shape of a molecule will affect its ability to pass through a lipid bilayer and the speed at which it will pass through.
    (b) Decide whether each of the following molecules will pass through a lipid bilayer. If so, state how fast it will pass through. (2.4) K/U T/I C
        (i) glucose
        (ii) glycerol
        (iii) water
        (iv) oxygen gas

68. Explain why ions such as chlorine, potassium, and sodium, despite being relatively small, cannot diffuse straight through the plasma membrane. (2.4) K/U T/I

69. (a) What molecule is used to obtain energy for active transport?
    (b) About how much of the total energy use of a cell is devoted to active transport? (2.4) K/U

70. Cells need a faster method than diffusion to supply water, amino acids, sugars, and ions. Identify the method they use, and explain how it works. (2.4) K/U T/I

71. Explain the methods of symport and antiport in secondary active transport pumps. (2.4) K/U

72. Describe what happens in a voltage-gated channel as it opens and closes. (2.4) K/U C

73. (a) Draw and label diagrams to show how endocytosis and receptor-mediated endocytosis work.
    (b) Describe how these processes are similar and different. (2.4) K/U C

74. Compare the following structures, noting both similarities and differences. Use lists, diagrams, and/or concept maps for your comparisons. (2.1, 2.4) K/U C
    (a) Golgi body and endoplasmic reticulum
    (b) plasma membrane and nuclear membrane
    (c) exocytosis and endocytosis
    (d) lysosome and vacuole
75. Where would you expect to find the greatest activity in each of the following cells? Name the organelles and structures that would be active, and explain your reasoning. (2.1, 2.4) T/I
    (a) active muscle cells in a swimming fish
    (b) cells in a growing seedling, which is preparing for mitotic division
    (c) cells in a spider's spinnerette organ, which produce large quantities of protein "silk"
76. (a) How does receptor-mediated endocytosis differ from regular endocytosis?
    (b) What kind of particle do you think would be most desired by a cell for receptor-mediated endocytosis? (2.4) K/U T/I

Analysis and Application

77. Would you expect muscle cells or fungal cells to have more mitochondria? Explain your reasoning. (2.1) K/U T/I
78. Ribosomes do not have a membrane. (2.1) K/U T/I
    (a) Explain why the functions of ribosomes do not require a membrane.
    (b) Ribosomes interact with organelles that do have a membrane. How is this beneficial?
79. Create an analogy to describe the functions and processes of the plasma membrane and organelles so that an elementary or middle school student could understand their functions. Explain any limitations that your analogy may have. (2.1) K/U A
80. If vesicles are constantly pinching off to carry proteins to the Golgi apparatus, why does the ER not eventually disappear? (2.1) K/U T/I
81. Alcohol and many drugs are metabolized in the liver. Explain why people who consume large amounts of these substances would have more smooth ER than a person who does not consume large amounts of these substances. (2.1) K/U T/I
82. Compare nanotechnology with traditional medicine. What are the benefits and problems associated with each? (2.3) K/U T/I A
83. Suppose that you accidentally place a freshwater fish in a saltwater tank. What would you expect to happen to the cells in the gills of the fish? Explain. (2.4) T/I A
84. Medical personnel use an intravenous saline solution to treat dehydration. Why do you think they use this saltwater solution instead of using pure water? (2.4) K/U T/I
85. In a small group, design an experiment to prove or disprove osmosis. You can use any materials that you think would be helpful. Some suggestions are: water, cornstarch, sugar, dialysis tubing or other semi-permeable membrane, and food colouring. Demonstrate your results to the rest of your classmates. (2.4) T/I C
86. What would happen if you watered a plant with a saltwater solution? (2.4) K/U T/I A

Evaluation

87. Which type of cell, prokaryotic or eukaryotic, do you think appeared earliest in evolution? Explain your reasoning. Use the Internet or other sources to help you formulate your argument. (2.1) T/I
88. What do you think life would be like if active transport was the only way materials could be moved through the membranes? (2.4) T/I A
89. A young girl presents with the following symptoms: failure to gain weight, wheezing sounds when breathing, and salty skin. Her doctor suggests three possibilities: Tay-Sachs disease, Friedreich's ataxia, and cystic fibrosis. Her parents want a second opinion. Given these potential diagnoses, evaluate the evidence supporting the diagnosis, indicating which part of the cell may be causing the problem, and provide the patient and her parents with a second opinion. (2.1, 2.2) T/I C A

Reflect on Your Learning

90. Were you surprised to learn how activities inside cells cause large-scale actions in and by the body? T/I
91. Consider your study of the plasma membrane. Have diagrams been helpful to you, or have you found point-form notes or concept maps more useful? What additional notes have you needed to make to help you remember the processes and components of the cell membrane? How did you better remember multi-step processes, such as the process of active transport: with a list or a diagram? K/U T/I
92. Teaching another person is an excellent way to cement your own knowledge. Develop a quiz with five multiple-choice questions, three true-false questions, and a concept map with blanks to fill in. Trade quizzes with a study partner. K/U T/I C

93. Think about how you could model a plasma membrane and its transport mechanisms. Pick one of the following options, and explain how you would represent the plasma membrane, including the movement required for the four transport mechanisms. T/I C A

Option A: You have 50 human actors and any props you need.

Option B: You have a machine shop and a technician to build your mechanisms.

Option C: You are building a model using food.

94. Pretend that you are the manager of the "cell team." You have been asked to decide which team member is the most valuable player. The candidates are lipid molecules, protein molecules, carbohydrates, and nucleic acids. Which candidate would you pick for the most valuable player? What would you say about the other candidates in your consolation remarks? T/I C A

Research

WEB LINK

95. Using the Internet and other sources, find examples of two biological activities where osmosis plays an important role. Give a brief explanation of how osmosis is important for each activity. T/I C A

96. Research ways that people with cystic fibrosis, such as Canadian triathlete Lisa Bentley, relieve or reduce their symptoms to improve their quality of life. T/I

97. In *A Wind in the Door* by Madeleine L'Engle, some of the characters shrink and go inside Charles Wallace's mitochondrion to try to discover what is making him tired and sick all the time. T/I

(a) What kind of mitochondrial disorder might Wallace have had?

(b) Research mitochondrial diseases. Describe at least one disease, its cause, and its symptoms.

98. What happens when the plasma membrane does not function properly? Problems with the permeability of the plasma membrane happen particularly to red blood cells. Research diseases associated with the permeability of the plasma membrane. List four of these diseases, and briefly describe their symptoms. T/I A

99. Over the past decade, intracellular research has led to many new findings about the Golgi body. Research and describe the roles of the Golgi body in health, immunity, and disease. T/I

100. Research the structure of bone tissue, and write a two-page report to summarize your findings. In your report, describe the structure and function of each type of bone cell. Also describe the extracellular material that gives bone tissue its strength. Include diagrams and information about the chemical/biological content of bone tissue, the nutrition that helps to keep bone tissue healthy, and diseases that can occur when bone tissue malfunctions. T/I C

101. Research the endoplasmic reticulum membrane, and compare its structure and function with the structure and function of the plasma membrane. T/I C

102. Research nanopipettes, an application of nanotechnology that is being explored for cell biology applications. What are the possible functions of nanopipettes? T/I C

103. Endocytosis of nanotubes has shown promise for the delivery of anticancer drugs to cancer cells, but is this a good idea? Using the Internet and other sources, find out how nanotubes enter cells and explain how cancer can be killed without damaging normal cells. Could these kinds of carrier systems pose a greater risk to patients than traditional methods? Weigh the pros and cons of nanoparticle technology for cancer treatment. T/I A

104. Prescriptions for antidepressants, medications to treat depression, have grown enormously in popularity in recent years, as well as in notoriety. There is now a minimum of six major groups of antidepressants, two of which are tricyclic antidepressants (TCAs) and selective serotonin reuptake inhibitors (SSRIs). Using the Internet and other sources, find out how the mechanism of action differs in these two types of drugs and what problematic side effects patients on these medications can encounter. Which class of drugs is preferable and why? Do the benefits outweigh the risks? T/I A

105. Can exercise keep you young at the cellular level? Many scientists believe that a loss of healthy mitochondria directly contributes to the aging process. Using the Internet and other sources, find out as much as you can about mitochondrial damage and aging. Does the existing evidence support the claim that exercise slows the aging process? Is one type of exercise more beneficial than another? T/I A

Molecules of Life

Sugars, fats, proteins … you have probably heard of these substances in relation to nutrition. Now that you have finished Unit 1, you should understand that they are not just important in food. They are critical to proper cell structure and function. In fact, our cells are composed of them. Glucose, or sugar, makes up starches, carbohydrates, and glycogen, which are involved in cell structure and the production of energy through cellular respiration. Fats, also known as lipids, also contribute to the structure of the cell—remember the lipid bilayer structure of the eukaryotic cell. As well, lipids are important for storing energy, and they play a role in cell signalling. Proteins, the workhorses of the body, are involved in almost all cell functions: structure, transport, defence against infection, delivery and receipt of messages, and movement.

Another group of important molecules are the nucleic acids. These molecules contain the following nitrogen-containing bases: adenine (A), guanine (G), cytosine (C), thymine (T), and uracil (U). They are the building blocks of life and are found in the DNA and RNA, which are the chemical codes for all of the genes that make us who we are.

Many scientists are interested in understanding the intrinsic characteristics, or properties, of biologically important molecules in order to recreate them—or parts of them—in a laboratory environment. The goal is to mimic their function and structure and to apply them to fields such as bioengineering, nanotechnology, environmental sciences, food sciences, and health and medicine.

In this Unit Task, you will choose a molecule that you find interesting. You will then research this molecule and some of its applications and build a model of it.

Goal

To research, understand, and build a model of a molecule of biological interest and to relate the role of macromolecules to the chemical and physical properties of the molecule

Equipment and Materials

- materials to represent molecular components (for example, Styrofoam balls, pipe wrap, and wire from coat hangers)
- access to the Internet
- samples of chosen compounds (if available)

Procedure

1. Use the Internet and other sources to research and choose a molecule that interests you. There are many different reasons why a molecule might capture your interest. Below are a few examples of molecules to start your thinking. Obtain approval from your teacher before you continue with Step 2. 🌐
   - sugars, which are key ingredients in many foods (**Figure 1**).

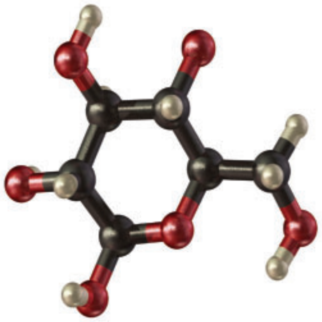


Figure 1 A glucose molecule

   - a pesticide such as DDT, which was banned because it bioaccumulates in organisms in food webs (**Figure 2**)

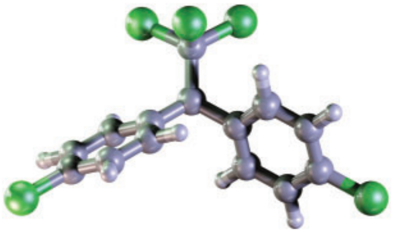


Figure 2 A DDT molecule

   - a scent molecule in perfume
   - an over-the-counter medicine, such as acetylsalicylic acid, or a prescription medicine, such as penicillin (**Figure 3**)

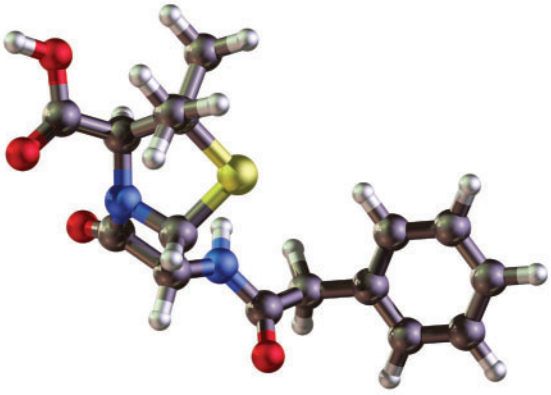


Figure 3 A penicillin molecule

- snake venom
- urushiol, which is the substance in poison ivy that can cause an itchy rash
- a protein such as rhodopsin, which is a membrane protein in the eye (**Figure 4**)

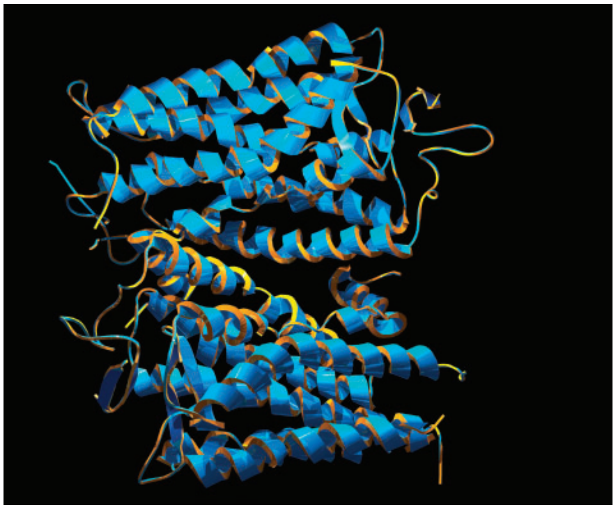


Figure 4 A rhodopsin molecule

2. Explain a biological role of the molecule you chose. Explain how your molecule is important to the successful functioning of the organisms that use it.
3. Conduct further research to determine the chemical and physical characteristics of your molecule.
4. Build a 3-D model to illustrate the chemical structure of your molecule. You can use whatever materials are appropriate for the size of your molecule. If the molecule is small (50 atoms or fewer), you may choose to build a model that shows every atom. If the molecule is large, however, you will only be able to depict its overall shape and structure with your model.
5. If possible, test and demonstrate the chemical and physical properties of your molecule.

Analyze and Evaluate

(a) Describe the size and shape of your molecule. How do these characteristics relate to its function? T/I A

(b) List the functional groups found in your molecule. How do these groups influence each of the following properties of the molecule, if at all? T/I
  (i) solubility
  (ii) reactivity
  (iii) physical shape
  (iv) overall function

(c) Relate these properties to the role of your substance in a living organism. T/I A

(d) How does this substance help an organism survive, if it does at all? T/I

Apply and Extend

(e) Brainstorm possible applications of the molecule you chose. In other words, how could your molecule be used to benefit people? A

(f) Are there possible biotechnology uses for your molecule? A

(g) Are there possible environmental applications of your molecule? A

WEB LINK

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

- ✓ Demonstrate understanding of what a biologically important molecule is.
- ✓ Recognize functional groups.
- ✓ Demonstrate knowledge of how functional groups are vital to life.

Thinking/Investigation

- ✓ Research applications of biologically important molecules in industry.
- ✓ Demonstrate understanding of ways that the molecule you chose can make a difference in your life.
- ✓ Relate the structure of your molecule to its function.

Communication

- ✓ Summarize your research in a clear, concise manner.
- ✓ Communicate your findings in a written or oral presentation.
- ✓ Build a model of your molecule.

Application

- ✓ Demonstrate your molecule, its functions, and its effects in a new context.
- ✓ Demonstrate an understanding of ways to modify your molecule for new uses, if possible.

UNIT 1 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following best describes the *p* orbitals? (1.1) K/U
   (a) five-lobed orbitals
   (b) three sets of two-lobed orbitals
   (c) spherical orbitals
   (d) four-lobed orbitals
2. Which of the following best describes a covalent bond? (1.1) K/U
   (a) transfer of electrons between a metal and a non-metal
   (b) transfer of electrons between two non-metals
   (c) sharing of electrons between a metal and a non-metal
   (d) sharing of electrons between two non-metals
3. What does water dissociate into? (1.2) K/U
   (a) ionic compounds
   (b) hydrogen and oxygen gas
   (c) hydroxide and hydrogen ions
   (d) vapour and steam
4. Which statement is correct? (1.3) K/U
   (a) Carbon can only form double bonds.
   (b) A double bond forms between two carbons, decreasing the number of bonds that can form with other atoms by one.
   (c) A double bond forms between three carbon atoms, decreasing the number of bonds that can form with other atoms by one.
   (d) A triple bond forms between two carbon atoms, decreasing the available bonding sites by three for each carbon.
5. What happens during hydrolysis? (1.3) K/U
   (a) H^+ is removed, and two molecules join.
   (b) OH^- is added, and two molecules split.
   (c) H_2O is removed, and two molecules join.
   (d) H_2O is added, and two molecules split.
6. Which property is responsible for the cohesiveness of water? (1.3) K/U
   (a) freezing point
   (b) density
   (c) strong hydrogen bonding
   (d) weak intermolecular forces
7. Which food is composed primarily of lipids? (1.4) K/U
   (a) apples
   (b) olive oil
   (c) eggs
   (d) wheat crackers
8. Which statement about fats is true? (1.4) K/U
   (a) Unsaturated fats are most common in plant seeds.
   (b) Saturated fats are not found in animal fats.
   (c) In plant and animal tissues, unsaturated and saturated fats are found in approximately equal proportions.
   (d) Fats that we eat provide about 4 kJ of energy per gram.
9. What do the functions of an enzyme rely on? (1.7) K/U
   (a) tertiary structure of the enzyme
   (b) quaternary structure of the enzyme
   (c) acidity of the surroundings
   (d) all of the above
10. Which type of cell needs more mitochondria than the other types of cells listed? (2.1) K/U
   (a) pancreatic cells
   (b) muscle cells
   (c) brain cells
   (d) stomach cells
11. What do ribosomes assemble? (2.1) K/U
   (a) lipids
   (b) proteins
   (c) nucleic acids
   (d) cell membranes
12. Cells must continuously take in certain molecules and ions, while keeping out others. Which organelle is responsible for doing this? (2.1) K/U
   (a) nucleus
   (b) lysosome
   (c) vesicle
   (d) plasma membrane
13. Which type of cell requires more rough endoplasmic reticulum than the other types of cells listed? (2.1) K/U
   (a) pancreatic cells
   (b) muscle cells
   (c) brain cells
   (d) skin cells
14. What does the "fluid" part of the fluid mosaic model represent? (2.2) K/U
   (a) constant movement of the hydrophilic tails in the interior of the membrane
   (b) thin layer of water that is sandwiched between the two layers of lipids
   (c) lipid molecules, which freely move among other lipids within the same half of the bilayer
   (d) free movement of cholesterol molecules within the membrane

15. The ____ component of the cell membrane works as a selective barrier, while the ____ component has several functions, such as transporting substances, recognizing other cells, and binding to other cells. (2.2) K/U
    (a) carbohydrate; nucleic acid
    (b) protein; lipid
    (c) lipid; protein
    (d) lipid; carbohydrate
16. What does the “mosaic” part of the fluid mosaic model represent? (2.2) K/U
    (a) proteins
    (b) lipids
    (c) cholesterol
    (d) functions
17. What is the name for the method of transport that allows water, amino acids, sugar, and ions to move through the plasma membrane at a sufficient rate? (2.4) K/U
    (a) facilitated diffusion
    (b) active transport
    (c) passive transport
    (d) endocytosis
18. An ion moving through a membrane channel in one direction provides energy to actively transport another molecule in the opposite direction. What is this process known as? (2.4) K/U
    (a) facilitated diffusion
    (b) exchange diffusion
    (c) antiport transport
    (d) cotransport
19. Which statement about the cell membrane is false? (2.4) K/U
    (a) It is composed of lipids that can spin, flex, and move within the membrane.
    (b) Approximately 50 % of the membrane consists of carbohydrates embedded in the lipid layers.
    (c) Proteins are embedded in the lipid layers.
    (d) Proteins are attached to the inner and outer surfaces.
20. Place the events of receptor-mediated endocytosis in the order in which they occur. (2.4) K/U
    1. The clathrin coat disappears.
    2. Receptors collect in a coated pit, covered with clathrin, on the cytosol side.
    3. Receptors recognize and bind specific molecules.
    4. Endocytic vesicles may fuse with lysosome, while receptors are recycled to the surface of the cell.
    5. Pits deepen and pinch free of the plasma membrane to form endocytic vesicles.

    (a) 2 1 3 5 4
    (b) 3 2 5 1 4
    (c) 4 1 5 2 3
    (d) 3 1 2 4 5

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

21. The 1*s* orbital is spherical. (1.1) K/U
22. Table salt contains two types of ions that your body needs: potassium and chloride. (1.1) K/U
23. Hydrogen bonds are weaker than ionic bonds. (1.1) K/U
24. An isomer is a molecule that has a different formula than another molecule. (1.1) K/U
25. Hydrogen bonding is responsible for the capillary action of water. (1.2) K/U
26. Water has a lattice crystalline structure in ice. (1.2) K/U
27. The ability of water to form bonds with other polar molecules is known as cohesion. (1.2) K/U
28. The high boiling point of water means that it remains in the liquid state over a wide range of temperatures. (1.2) K/U
29. Water has a higher surface tension than oil. (1.3) K/U
30. One function of fats is to waterproof leaves. (1.4) K/U
31. Saturated fats stay fluid at lower temperatures than unsaturated fats. (1.4) K/U
32. Cellulose is a carbohydrate because it has a formula with the ratio $(CH_3O)_n$. (1.4) K/U
33. Triglycerides have more kilojoules per gram than trisaccharides do. (1.4) K/U
34. Enzymes are made of lipids. (1.7) K/U
35. Eukaryotes do not have a nucleus. (2.1) K/U
36. Proteins are synthesized by ribosomes in the smooth endoplasmic reticulum. (2.1) K/U
37. The endomembrane system consists of interacting organelles that are located between the nuclear membrane and the plasma membrane. (2.1) K/U
38. Endosymbiosis describes how both mitochondria and nuclei may have evolved from cells that were engulfed by other cells. (2.1) K/U
39. The dominant lipids that are found in membranes are glycolipids. (2.2) K/U
40. As well as lipids, a group of compounds called sterols influence membrane fluidity. (2.2) K/U
41. Proton pumps move hydrogen ions from the outside of a cell to the cytosol. (2.4) K/U
42. In symport, a substance is transported in the same direction as the concentration gradient; in antiport, a substance is transported in the opposite direction to the concentration gradient. (2.4) K/U
43. ATP is needed for passive transport to occur. (2.4) K/U

UNIT 1 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which compound must your body synthesize because it cannot be obtained through food consumption? (1.1) K/U
   (a) nucleic acids
   (b) lipids
   (c) carbohydrates
   (d) proteins
2. Which of the following best describes a hydrolysis reaction? (1.1) K/U
   (a) a reaction in which small molecules react to produce a large polymer and water
   (b) a reaction between an acid and a base in which a salt (and often water) is produced
   (c) a reaction in which water molecules are split to degrade a large polymer
   (d) a reaction in which one of the reactants gains an electron
3. Molecules of water tend to stay close together, due to extensive hydrogen bonding. What is this property of water called? (1.2) K/U
   (a) surface tension
   (b) adhesion
   (c) cohesion
   (d) capillary action
4. The pH of a urine sample was found to be 8.1. Based on this pH value, how should the urine be classified? (1.2) K/U
   (a) strong acid
   (b) strong base
   (c) weak acid
   (d) weak base
5. What may be formed by carbon atoms within biochemical molecules? (1.3) K/U
   (a) rings, straight chains, and branched chains
   (b) rings, straight chains, and networks
   (c) rings and straight chains only
   (d) straight chains, networks, and branched chains
6. Which hydrocarbon has one carbon atom bonded to four hydrogen atoms? (1.3) K/U
   (a) ethane
   (b) methane
   (c) propane
   (d) butane
7. Which diagram in **Figure 1** represents a building block of starch? (1.4) K/U

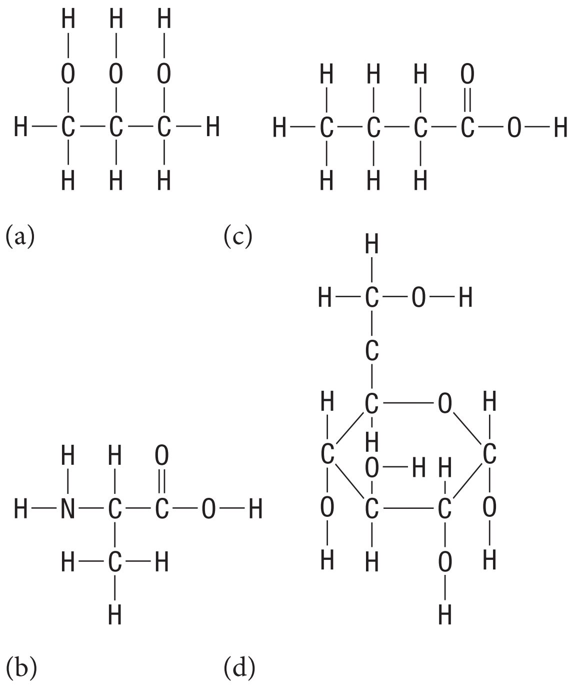


Figure 1

8. What is the difference between saturated fats and unsaturated fats? (1.4) K/U
   (a) Saturated fats are produced by plants, and unsaturated fats are produced by animals.
   (b) Saturated fats are produced by animals, and unsaturated fats are produced by plants.
   (c) Saturated fats contain glycerol, whereas unsaturated fats do not.
   (d) Margarine is a saturated fat, and butter is an unsaturated fat.
9. What is an amphipathic molecule? (1.4) K/U
   (a) primary lipid of a cell membrane
   (b) molecule that is composed of saturated fatty acids with single bonds in their carbon chain
   (c) molecule that contains both hydrophilic and hydrophobic regions
   (d) lipid that is composed of four carbon rings
10. Which protein structure results from hydrogen bonding between different parts of the same amino acid backbone? (1.5) K/U
   (a) primary structure
   (b) secondary structure
   (c) tertiary structure
   (d) quaternary structure

11. Which statement about nucleotides is correct? (1.5) K/U
    (a) A nucleotide consists of three subunits linked together by covalent bonds.
    (b) A nucleotide consists of five subunits linked together by covalent bonds.
    (c) A nucleotide consists of three subunits linked together by ionic bonds.
    (d) A nucleotide consists of five subunits linked together by ionic bonds.
12. Which of the following are functions of proteins? (1.5) K/U
    (a) enzymatic activity, carrying genetic material, and transport
    (b) enzymatic activity, carrying genetic material, and cell recognition
    (c) enzymatic activity, transport, and cell recognition
    (d) carrying genetic material, transport, and cell recognition
13. Which statement best describes the process of competitive inhibition? (1.7) K/U
    (a) The products of the reaction block the active site of the enzyme.
    (b) The products of the reaction bind to a site other than the active site of the enzyme, but still block enzyme activity indirectly.
    (c) The substrate and cofactors compete for the active site.
    (d) The inhibitor binds to and directly blocks the active site of the enzyme.
14. Which statement best describes the process of non-competitive inhibition? (1.7) K/U
    (a) The products of the reaction block the active site of the enzyme.
    (b) The products of the reaction bind to a site other than the active site of an enzyme, but still block enzyme activity indirectly.
    (c) The substrate and cofactors compete for the active site.
    (d) The inhibitor binds to and directly blocks the active site of the enzyme.
15. Which organelle resembles a bacterial cell? (2.1) K/U
    (a) smooth endoplasmic reticulum
    (b) nucleus
    (c) rough endoplasmic reticulum
    (d) mitochondrion
16. What is the main function of a mitochondrion? (2.1) K/U
    (a) ATP production
    (b) cell repair
    (c) transport
    (d) membrane functions
17. Which organelle probably evolved in a similar way to chloroplasts? (2.2) K/U
    (a) lysosome
    (b) vesicle
    (c) mitochondrion
    (d) vacuole
18. Which statement is correct? (2.2) K/U
    (a) Membrane lipids are polar molecules.
    (b) The higher the proportion of saturated lipids, the more fluid a membrane will be.
    (c) Molecules of cholesterol are found integrated into membranes.
    (d) A glycolipid is a membrane component that is bound to an amino acid.
19. How do the various membranes of a cell differ? (2.2) K/U
    (a) Lipids are found only in certain membranes.
    (b) Certain proteins are unique to each membrane.
    (c) Only certain membranes are constructed from molecules with dual solubility.
    (d) Only certain membranes of a cell are selectively permeable.
20. When a plant cell is placed in a hypotonic solution, what does the cell wall prevent from happening? (2.4) K/U
    (a) plasmolysis
    (b) diffusion
    (c) active transport
    (d) the cell from bursting
21. Which statement about active transport is true? (2.4) K/U
    (a) In active transport, substances move with the concentration gradient and the cell expends energy.
    (b) Active transport depends on membrane proteins and is therefore specific for certain substances.
    (c) Active transport increases in speed as more energy is supplied to the cell.
    (d) The rate of active transport decreases once there is a high concentration of substrate in the cell.
22. Which of the following is absolutely necessary for diffusion to occur? (2.4) K/U
    (a) cell
    (b) lipid bilayer
    (c) selectively permeable membrane
    (d) concentration gradient

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

23. Isotopes are different forms of different elements, with different numbers of neutrons. (1.1) K/U
24. A difference in electronegativity results in bond polarity. (1.1) K/U

25. Oxidation is the loss of electrons; reduction is the gain of electrons. (1.1) K/U
26. When polar molecules dissolve in solution, the surrounding water increases the electrostatic interactions between them. (1.2) K/U
27. Strong acids and strong bases dissociate completely in water. (1.2) K/U
28. A buffer is a weak acid or base that can compensate for changes in a solution to maintain the proper pH level. (1.3) K/U
29. Nitrogen atoms form the backbone of biological molecules. (1.3) K/U
30. Functional groups are small reactive groups that are usually ionic or strongly polar. (1.3) K/U
31. Osmosis is the facilitated movement of water molecules across a membrane. (2.4) K/U
32. A monosaccharide consists of two single sugar subunits. (1.4) K/U
33. All proteins are polymers that are composed of amino acid polymers. (1.5) K/U
34. Enzyme activity is affected by substrate and enzyme concentrations, temperature, and pH. (1.7) K/U
35. Animal cells contain different plastids than plant cells contain. (2.1) K/U
36. Compared with integral membrane proteins, peripheral membrane proteins are more likely to be recognition proteins. (2.2) K/U
37. The selective permeability of a cell membrane is due to the hydrophobic core formed by the lipid tails. (2.2) K/U
38. Membrane proteins have three specific transport functions. (2.2) K/U
39. The Na$^+$/K$^+$ pump is responsible for maintaining the membrane potential across a cell membrane. (2.4) K/U
40. Exocytosis moves aggregate molecules into a cell. (2.4) K/U
41. The plasma membrane is responsible for pinocytosis and phagocytosis. (2.4) K/U

Match each term on the left with the most appropriate description on the right.

42. (a) fat
    (b) disaccharide
    (c) phospholipid
    (d) steroid
    (e) wax
    (f) polysaccharide

    (i) four fused carbon rings
    (ii) long chain of sugar monomers
    (iii) two fatty acids combined with glycerol, and a phosphate group combined with an alcohol
    (iv) long-chain fatty acid
    (v) substance derived from glycerol and three fatty acids
    (vi) two monosaccharides (1.4) K/U

43. (a) osmosis
    (b) facilitated diffusion
    (c) phagocytosis
    (d) pinocytosis
    (e) receptor-mediated endocytosis
    (f) diffusion

    (i) movement of a molecule from an area of high concentration to an area of low concentration
    (ii) cells internalize molecules into a cell by the inward budding of vesicles possessing receptors specific to the molecule being transported
    (iii) movement of water from a hypotonic solution into a hypertonic solution across a selectively permeable membrane
    (iv) process in which liquid droplets are ingested by living cells
    (v) large particles are enveloped by the plasma membrane and internalized
    (vi) diffusion of molecules across the plasma membrane with the assistance of transport proteins (2.4) K/U

Write a short answer to each question.

44. (a) List three characteristics of ionic bonds.
    (b) Give three examples of ionic bonds in biochemistry. (1.1) K/U
45. Tritium is a radioactive isotope that is useful in diagnostics. It consists of a hydrogen atom with a mass of 3 u (atomic mass units). How many neutrons does it have? (1.1) K/U T/I
46. List three unique properties of water, and give an example that shows how each property is significant for living things. (1.2) K/U T/I
47. (a) Explain how a buffer moderates pH.
    (b) Discuss the significance of buffers as they pertain to biological processes and living things. (1.2) K/U
48. (a) Identify four functional groups, and describe the properties of each.
    (b) For each functional group you identified, give two examples of chemicals in which the functional group can be found. (1.3) K/U

49. Compare and contrast dehydration reactions with hydrolysis reactions. (1.3) K/U T/I

50. Draw a lipid bilayer, and show how the heads and tails of the lipid molecules align themselves. Label the hydrophilic section and the hydrophobic section. (1.4) K/U C

51. (a) Write a short summary to explain the process in which a triglyceride is formed. Include a drawing that shows the structural formula for the formation of a triglyceride molecule.
    (b) What type of reaction is this? Explain your reasoning. (1.4) K/U C

52. Identify and draw the types of bonds involved in each synthesis reaction. (1.4, 1.5) K/U C
    (a) Two monosaccharides join to form a disaccharide.
    (b) Two amino acids join to form a dipeptide.
    (c) Two nucleic acids join to form a strand of DNA.

53. List six functions of proteins, and give one specific example of each. (1.5) K/U

54. In non-competitive inhibition, specific molecules bind to an enzyme to change its conformation and disable it. Distinguish between reversible inhibition and irreversible inhibition. (1.7) K/U

55. List four factors that affect the functions of enzymes. (1.7) K/U

56. List two components that are assembled in the nucleolus during the production of ribosomes. (2.1) K/U

57. Identify three different types of plastids, and list a function of each. (2.1) K/U

58. (a) What is the main function of lysosomes?
    (b) Do you think animal cells could survive without lysosomes? Explain your reasoning. (2.1) K/U T/I

59. (a) Which protein is affected by the gene that causes cystic fibrosis?
    (b) What role does this protein play in good health?
    (c) How does the mutated form of this protein affect people with cystic fibrosis? (2.2) K/U

60. (a) Identify the energy source that is used by secondary active transport pumps.
    (b) Explain how this energy source is established. (2.4) K/U

Understanding

61. Carbon-12 and carbon-13 are stable isotopes, whereas carbon-14 decays. Describe the changes that radioactive carbon undergoes when it decays. (1.1) K/U

62. Complete **Table 1** by entering the number of protons, neutrons, and electrons for each atom or isotope. (1.1) K/U

Table 1

Electrons	Protons	Neutrons	Symbol
			^{12}C
11	11	12	
17			^{35}Cl
	1	0	^{1}H

63. Water has been called "the solvent of life." Explain this description. (1.2) K/U A

64. Explain how you could measure the strength of an acid. (1.2) K/U T/I A

65. Carbon has four valence electrons. How does this facilitate the great diversity of hydrocarbons that exist in nature? Illustrate your explanation with drawings. (1.3) K/U T/I C A

66. Many nutritionists recommend eating a low-fat diet. Why do they not recommend eating a no-fat diet? (1.4) K/U T/I

67. Scientists have created levo-sugar, which is an isomer of sucrose (table sugar). The structure of levo-sugar is a mirror image of the structure of sucrose. Would you expect the enzymes that digest sucrose to be equally effective in digesting levo-sugar? Explain your reasoning. (1.4) K/U T/I A

68. (a) Which type of fat contains kinks in the fatty acid chains?
    (b) How are these kinks created?
    (c) What is the biological significance of these kinks? (1.4) K/U

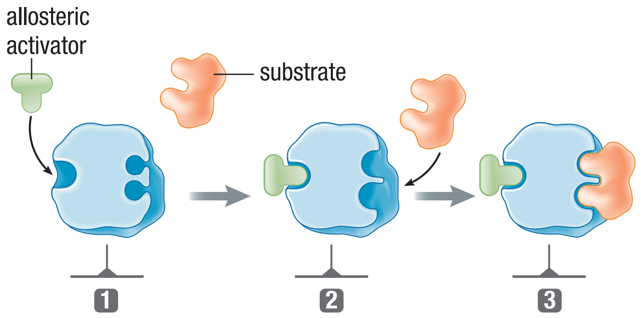
69. Draw a diagram to show the dehydration reaction that occurs when two peptides bond together. (1.5) K/U C

70. Explain why guanine does not pair with thymine and why cytosine does not pair with adenine. (1.5) K/U

71. A fragment from a strand of DNA has the following nitrogenous base sequence: GATTAAC. What would be the nitrogenous base sequence for the complementary antisense strand? (1.5) K/U T/I A

72. Distinguish between competitive inhibition and non-competitive inhibition, in terms of enzymatic function. (1.7) K/U

73. Describe each stage of allosteric activation and allosteric inhibition in **Figure 2**. (1.7) K/U



(a) allosteric activation

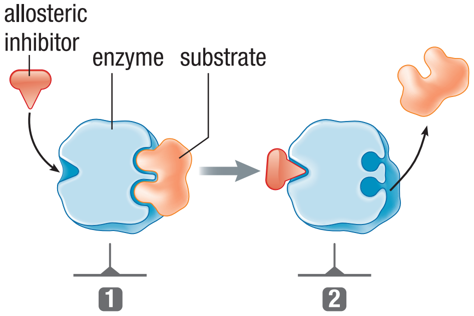


Figure 2

74. **Figure 3** shows enzyme activity over a range of temperatures. Consider an enzyme with an optimal temperature of 37 °C. (1.7) K/U T/I
    (a) Based on the information presented in Figure 2, at what temperature will the activity of this enzyme decrease?
    (b) At what temperature will the activity of this enzyme likely be completely eliminated?

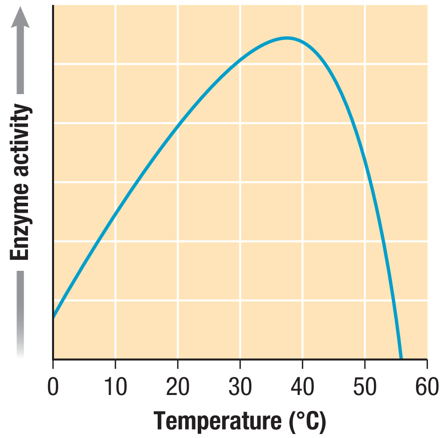


Figure 3

75. Compare and contrast the functions of the nuclear membrane with the functions of the plasma membrane. (2.1) K/U T/I

76. Use **Figure 4** to answer the following questions. (2.1) K/U
    (a) Identify the organelle shown.
    (b) What are the functions of this organelle?
    (c) Identify structure A. What is its function?
    (d) Identify structure B. What is its function?

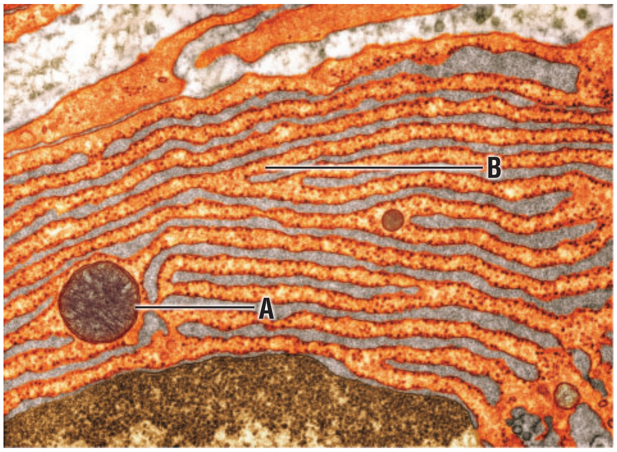


Figure 4

77. (a) Identify the organelle shown in **Figure 5**.
    (b) What is the function of this organelle?
    (c) According to biologists, how did this organelle likely evolve to its present form? (2.1) K/U

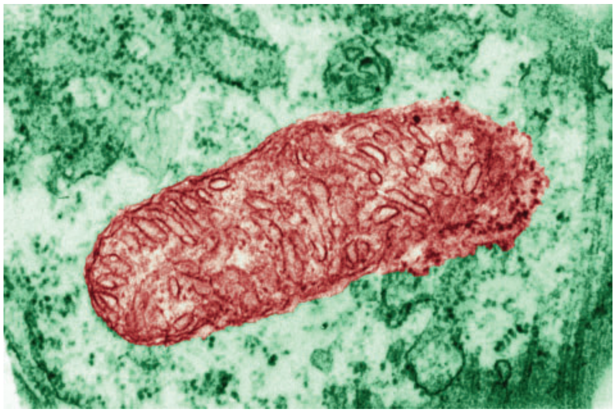


Figure 5

78. Create a concept map to show the four major functions of membrane proteins. Include a description of each function, as well as an example. (2.2) K/U T/I C

79. Why is it important that the lining of the lungs and intestinal tract be hydrated? (2.2) K/U

80. Compare and contrast the functions of channel proteins with the functions of carrier proteins, as related to their involvement in facilitated diffusion. (2.4) K/U T/I

81. Describe the process of symport transport. Use a labelled diagram to support your description. (2.4) K/U T/I C

82. (a) Draw a phosphate group, and briefly describe the various applications of phosphate in the body.
    (b) Create a table or bulleted list of the compounds that contain phosphate groups and their functions. (1.3, 1.4, 1.5, 2.2, 2.4) K/U

Analysis and Application

83. During a genetic engineering experiment, a researcher injected cells with DNA molecules that contained a radioactive isotope of phosphorus. Explain why the researcher did this. (1.1) K/U T/I

84. Metabolic acidosis is the decrease in blood pH that results when excessive amounts of acidic substances are released into the blood. Explain how buffers are able to prevent this from occurring under normal circumstances. (1.2) K/U T/I

85. How do the bonding properties of water benefit freshwater fish during extremely cold winters? (1.2) K/U T/I A

86. Lactulose is a synthetic dissacharide sugar that is formed when one molecule of galactose and one molecule of fructose are joined in a dehydration reaction (**Figure 6**). (1.3) K/U C
    (a) Use diagrams to illustrate the reverse reaction, in which lactulose is split by hydrolysis, producing one molecule of galactose and one molecule of fructose.
    (b) Use this example to explain why hydrolysis is considered to be the "reverse" of dehydration.

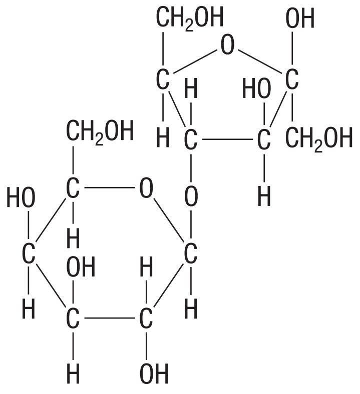


Figure 6

87. The breakdown of carbohydrates and proteins cannot take place in the absence of water. Explain why. (1.4) K/U

88. (a) Describe the four structural levels of a protein.
    (b) Which structural level would be the first to be affected by each situation below?
        (i) a temperature that is significantly above normal body temperature
        (ii) lack of a particular amino acid
        (iii) a contaminant that interferes with S–S bonding
        (iv) an unusually low or high pH
        (v) conditions that interfere with dehydration reactions (1.5) K/U T/I A

89. Would you expect a long straight protein to function as an enzyme? Explain your reasoning. (1.5, 1.7) K/U T/I

90. In some organisms, isoleucine can be synthesized in a multi-step procedure (a series of reactions), beginning with a molecule of threonine (see Figure 7, page 54). Explain how, in this pathway, the accumulation of isoleucine as an end product can inhibit further production of isoleucine. (1.7) K/U

91. Cheese making is a process that requires the enzymes chymosin and pepsin to create curd. Suppose that you are trying to make your own cheese, but the curd is not forming properly. What factors might you measure to see if enzyme activity is the reason for the problem? (1.7) K/U T/I

92. Explain why minerals such as magnesium oxide and zinc oxide are often added to multivitamins. (1.7) K/U T/I

93. Design an experiment to determine the optimal conditions for amylase (the enzyme that breaks down starch). Include a list of the equipment and materials you would need, and describe the procedure. (1.7) T/I C

94. What do you expect would be an ideal temperature and pH environment for enzyme activity in the human stomach? Justify your answer. (1.7) K/U T/I

95. Mitochondrial membranes are composed of 76 % protein and 24 % lipid. Myelin sheaths are composed of 18 % protein and 82 % lipid. Explain how these differences in composition enable each structure to perform its specific function. (2.2) K/U T/I

96. (a) What is the function of cholesterol in the lipid bilayer membrane of animal cells?
    (b) What is the function of carbohydrates in the lipid bilayer membrane?
    (c) What are two ways that proteins may be involved in the plasma membrane? What do you expect would happen if there was a mutation in the membrane proteins of the plasma membrane? (2.2) K/U T/I

97. If the plasma membrane were turned inside out, would it still function correctly? (2.2) T/I

98. The waved albatross feeds exclusively on marine organisms and has no access to fresh water. It has specialized nasal glands to excrete excess salt **(Figure 7)**. Consider the cellular mechanisms that might be involved in the production of the highly concentrated salt solution released by this bird. (2.4) K/U T/I A
    (a) Would the production of the concentrated salt solution be an active process or a passive process? Explain your reasoning.
    (b) What type of membrane transport mechanism might be involved?
    (c) What problems might arise if the albatross were unable to rid itself of excess salt?

Figure 7

99. (a) Compare and contrast exocytosis with endocytosis.
    (b) For each of the following situations, decide whether exocytosis or endocytosis would be required. Explain your reasoning.
        (i) flower cells that are involved in nectar production
        (ii) cells that line the small intestine
        (iii) cells of the mammary glands (2.4) K/U T/I A

100. Would you expect a starch molecule to be able to move through a plasma membrane via simple diffusion? Explain why or why not. (1.4, 2.4) K/U T/I

Evaluation

101. Scientists have been able to create a very simple protein that consists of a single polypeptide with one of each of the 20 amino acids. (1.5) K/U T/I C
    (a) What are some of the possible advantages and disadvantages of mass-producing this protein as a food?
    (b) Would you eat this protein? Explain why or why not.

102. People who are lactose intolerant do not produce lactase, the enzyme that is required to break down this milk sugar. (1.4, 1.7) K/U T/I
    (a) Describe some ways that lactose-intolerant people could deal with this problem.
    (b) Suggest approaches that scientists could use to develop other options for lactose-intolerant people.

103. How difficult do you think it would be to synthesize an enzyme in a laboratory? Explain your reasoning. (1.5, 1.7) K/U T/I A

104. What materials would you use to create a model of a lipid bilayer? Justify your choice of materials, and discuss the strengths and limitations of your proposed model. (For example, jelly is too formless. Strings of fabric do not rotate and flip as real phospholipids would.) (1.4, 2.2) T/I C

105. Brainstorm another suitable name for the fluid mosaic model. Explain how your choice in name reflects the behaviour of proteins within a lipid membrane. (2.2) T/I A

106. Nanotechnology researchers are attempting to create tiny "nanobots" that can perform tasks at the cellular level. What do you think is the greatest challenge that nanotechnologists face in creating such small machines? (2.3) K/U T/I

107. Is there a limit on how big a cell can be? Explain why or why not. (2.4) K/U T/I

Reflect on Your Learning

108. Why do you think it is essential for people who study biology to have an understanding of the various kinds of bonds that occur within and between molecules? T/I

109. What practical application do you think an understanding of acids and bases might have for people who work in the fields of biology and physiology? T/I A

110. (a) What information in this unit did you know before you started working on this unit?
    (b) What information in this unit was completely new to you?
    (c) How has your thinking about the chemistry of biology changed, based on what you have learned? T/I

111. What aspect of biochemistry did you find the most interesting? Explain your answer. T/I

112. Nanotechnology in medicine could change the way medical tests, and health care in general, are delivered. T/I
   (a) Does nanotechnology in medicine concern you, or are you excited about the possibilities?
   (b) Would you be willing to have a nanobot deliver medication in your body? Explain your answer.

Research

WEB LINK

113. Use the Internet and other sources to research at least five different videos and animations that illustrate the following information:
   - how carbon bonds to other atoms
   - the atomic orbitals of carbon
   - how the electrons in a carbon atom bond with other atoms to form molecular orbitals

   (a) Create a three-column KWL (Known, Want to Know, Learned) chart in your notebook. Before and after watching each video you research, complete an entry in your KWL chart.
   (b) Using the information you collect, create a pamphlet or poster that illustrates the key information about carbon bonding. K/U T/I C A

114. Cryobiology is the study of any biological material or system (such as proteins, cells, tissues, organs, or organisms) that is subjected to a temperature below normal (ranging from moderately hypothermic conditions to cryogenic temperatures). While some aspects of cryobiology seem futuristic, one aspect—cryosurgery—is currently being used in medicine. Use the Internet and other sources to research cryosurgery, and then report your findings in a short newspaper-style editorial. Answer the following questions in your editorial:
   - What is cryosurgery?
   - How does it work?
   - What conditions can be treated with cryosurgery?
   - What are the advantages and disadvantages of cryosurgery? T/I C A

115. Forensic biology is the application of biology to law enforcement. It can include sub-disciplines such as anthropology, botany, entomology, ondontology, and DNA or protein-based techniques. Using the Internet and other sources, research how law enforcement uses these sub-disciplines in crime scene investigations. What information can each sub-discipline provide? Write a newspaper-style report to summarize your findings. T/I C A

116. Conduct online research to find out what efforts have been made to create a synthetic lipid bilayer cell membrane. T/I C A
   (a) Create a graphic organizer that shows the progress in this field of study to date.
   (b) Write a brief report to summarize your findings, and present it to your classmates in a format of your choice. Answer the following questions in your report:
      - What materials have scientists used to create a synthetic lipid bilayer cell membrane?
      - How successful have these materials been?
      - Why are scientists interested in creating a synthetic lipid bilayer cell membrane?

117. Protein is an important macronutrient that the human body requires for many biological processes. Although the body can synthesize some amino acids, there are some essential amino acids that must be obtained from food. Using the Internet and other sources, research the eight essential amino acids. T/I C A
   (a) Use your findings to answer the following questions for each essential amino acid. Present your answers in table format.
      - What is the role of the amino acid in the human body?
      - What are two food sources for the amino acid?
      - What results from a deficiency in the amino acid?
   (b) Based on your research, can you make a general statement about the dietary requirements of an adult for the eight essential amino acids? Explain why or why not.

118. Sugar consumption is often cited as one of the contributing factors to obesity and diabetes in North American children and adults. Artificial sweeteners are suggested as an alternative. Using the Internet and other sources, find out as much as you can about two artificial sweeteners, including how they differ from sugar, how many times as sweet they are as sugar, and how they are metabolized by the body. Which do you think is a better choice: sugar or artificial sweeteners? Create a poster explaining your choice. T/I C A

119. Olestra is an artificial fat substitute that contains no fat and does not add calories or cholesterol when added to foods. Using the Internet and other sources, research fat substitutes. Write a brief report that contains answers to the following questions:
   - What are fat substitutes, and how are they chemically different from fats?
   - What are the three major types of fat substitutes?
   - What are the possible impacts of fat substitutes on health?
   - What are the advantages of fat substitutes? T/I C A

UNIT 2

Metabolic Processes

OVERALL EXPECTATIONS

- analyze the role of metabolic processes in the functioning of biotic and abiotic systems and evaluate the importance of an understanding of these processes and related technologies to personal choices made in everyday life
- investigate the products of metabolic processes such as cellular respiration and photosynthesis
- demonstrate an understanding of the chemical changes and energy conversions that occur in metabolic processes

BIG IDEAS

- All metabolic processes involve chemical changes and energy conversions.
- An understanding of metabolic processes enables people to make informed choices with respect to a range of personal, societal, and environmental issues.

UNIT TASK **PREVIEW**

In the Unit Task, you will explore applications of photosynthesis and respiration. You will also explore factors that affect photosynthesis and respiration and consider the implications of altering these factors.

The Unit Task is described in detail on page 252. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

FOCUS ON **STSE**

FANTASTIC FERMENTATION

For thousands of years, the process of fermentation has been used to produce foods and beverages. The earliest of these—beer, wine, and leavened bread—were produced using yeast. The alcohol in fermented beverages often made them safer to drink than water from local supplies, which may have been contaminated with pathogens. Evidence of beer production traces back to ancient Babylonian civilization as early as 7000 BCE. At the time, microbes such as yeast were unknown, and the transformation of basic food ingredients into fermented foods was a mystery that was often considered a miracle.

Bread making, alcohol production, and cheese making are just a few examples of fermentation used in food production. Other examples are chocolate, vanilla, soy sauce, tea, idili, sosa, kimchi, vinegar, sauerkraut, miso, bagoog, yogurt, and kefir. Civilizations have used fermentation to produce important foods from grains, beans, leaves, fruits, honey, milk, fish, and red meat. Almost every culture has a tradition of foods that require fermentation. Cheeses were made with fermentation processes involving bacteria and mould that we still use today. We now understand many of the specific biochemical pathways involved in fermentation as well as the biology of micro-organisms such as yeast and bacteria. In fact, in 1996, yeast was the very first eukaryotic organism to have its entire genome sequenced.

More recently, scientists have used their knowledge of fermentation to produce a new range of substances. Fermentation is used to add nutritional value to foods. For example, moulds have been used in industrial fermentation to make vitamins B-2 (riboflavin) and B-12. Fermentation is also used in the production of some antibiotics. Bio-ethanol, a fuel that is used primarily in Brazil, is made from fermented sugar. Crops that can be grown specifically as a sugar energy source include sugar cane, corn, and wheat. Bio-ethanol has the promise of being a sustainable fuel source, but there is concern that it will require too much of our food supply, cropland, and fertilizers. This is all just the beginning. As scientific advances are made, plants, yeast, and other organisms will be used to produce many more useful, sustainable products. They might also be capable of destroying unwanted waste in environmentally friendly ways.

Questions

1. In Canada, there is a great diversity of people and cultures. Make a list of five fermented foods that we are able to enjoy because of our diversity. Which have you eaten?
2. Why do you think certain fermentation foods have remained popular over generations? How do you think so many cultures were able to discover and make use of the process of fermentation?
3. We use living organisms such as yeast and crops to produce valuable substances such as fuel. What advantages does this process have over other production methods?
4. Humans have the ability to influence the fermentation process of food and drinks. What factors in the process might we be able to alter?

UNIT 2 ARE YOU READY?

CONCEPTS

- contrast cell structure in plants and animals
- understand atomic theory and chemical bonding
- differentiate carbohydrates, lipids, proteins, nucleic acids, and enzymes
- describe diffusion, osmosis, and active transport
- describe the flow of energy in photosynthesis and cellular respiration in ecosystems
- contrast exothermic and endothermic reactions
- recognize oxidation and acid/base reactions
- understand the laws of conservation of energy

SKILLS

- select and use suitable instruments to carry out investigations precisely
- use chemical reagents, lab glassware, and heating apparatus in an appropriate and safe manner
- calculate the energy required to heat a specific volume of water
- balance simple chemical equations
- write an equation for a simple chemical reaction
- draw structural diagrams of biological molecules
- describe a procedure to test for the presence of a specific chemical

---

Concepts Review

1. As energy flows through a terrestrial ecosystem, there is less energy at each higher trophic level. Explain how energy can be lost from an ecosystem as it is converted from one form to another. K/U
2. Explain why most of the energy that is used by living organisms is supplied by green plant life. K/U
3. Explain how the double lipid bilayer of the cell membrane plays a role in each of the following. K/U
   (a) transport
   (b) cell–cell recognition
   (c) structural stability of the cell
4. Water molecules are formed from oxygen gas and hydrogen gas. K/U
   (a) In this reaction, what old bonds break and new bonds form?
   (b) Which process (bond breaking or bond formation) requires an input of energy?
   (c) When is additional energy required during the reaction?
5. What effect do changes in the concentration of H^+ and OH^- ions have on the pH of a solution? K/U
6. Draw a diagram to illustrate how carboxyl and amino groups can act as both acids and bases in a chemical reaction. K/U C
7. If the concentration of H^+ inside a cell is 0.5 mol/L and the concentration of H^+ outside a cell is 1.5 mol/L, in which direction are the H^+ ions likely to diffuse if suitable pathways are opened in the cell membrane? T/I
8. What role does oxygen play in plant cells? K/U
9. Explain how each of the following examples represents a transformation of energy from one form to another. T/I
   (a) A light bulb in a lamp is turned on.
   (b) Green plants make food.
   (c) A runner feels overheated.
10. Match the cell structures on the left with their corresponding functions on the right. K/U
    (a) chloroplast
    (b) mitochondrion
    (c) nucleus
    (d) membrane
    (i) is responsible for ATP production
    (ii) is necessary for photosynthesis
    (iii) encloses cell and regulates concentration of solutes
    (iv) contains a cell's DNA
11. Match each term on the left with the most appropriate description on the right. K/U
    (a) exothermic
    (b) work
    (c) energy
    (d) chemical bond
    (e) endothermic
    (i) attraction between atoms that forms chemical substances
    (ii) force applied over a distance
    (iii) chemical reaction that releases thermal energy
    (iv) chemical reaction that absorbs thermal energy
    (v) ability to do work on a physical system
12. State whether each kingdom consist of producers, consumers, or both. K/U
    (a) archaea
    (b) eubacteria
    (c) protista
    (d) fungi
    (e) plants
    (f) animals

13. Why are even small ions unable to diffuse across a cell membrane? K/U

14. During a change of state from liquid water to water vapour, thermal energy is continuously added to the water. The temperature of the water, however, remains constant at 100 °C. How can this be explained in terms of the law of conservation of energy? K/U T/I

15. Marine iguanas (**Figure 1**) are "cold-blooded." They need to warm up in the sunlight after feeding underwater. K/U T/I
    (a) How is the colour of the iguana beneficial?
    (b) Why do "warm-blooded" penguins and seals not have to warm up in the sunlight after being in the water?
    (c) How might this difference between the species influence their overall food requirements?

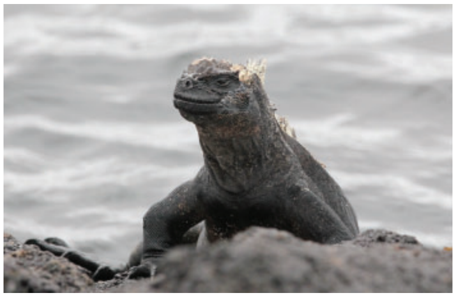


Figure 1

16. The lava cactus plant (**Figure 2**) lives in an extremely dry environment. What visible adaptations does it have for survival? Suggest other possible adaptations at the microscopic or cellular level. K/U T/I

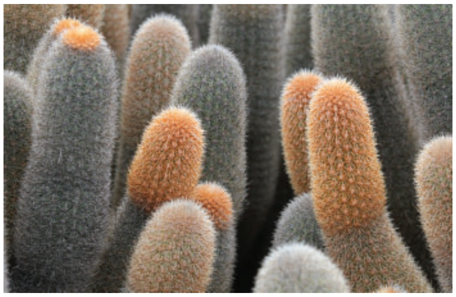


Figure 2

Skills Review

17. As a student, you have the opportunity to research scientific topics on the Internet. When using the Internet, what are some of the criteria you can use to determine whether the website is trustworthy? T/I

18. Rewrite the following chemical reactions as properly balanced chemical equations. T/I C
    (a) photosynthesis: $CO_2 + H_2O \rightarrow C_6H_{12}O_6 + H_2O + O_2$
    (b) burning ethanol: $C_2H_5OH + O_2 \rightarrow CO_2 + H_2O$

19. (a) Draw the structural diagram of glucose and ethanol.
    (b) How many C–H bonds are in each?
    (c) How many O–H bonds are in each?
    (d) How many C–C bonds are in each?
    (e) How many C–O bonds are in each? K/U C

20. If it takes 4.18 J of energy to warm 1 g of water by 1 °C, calculate the amount of energy needed to raise the temperature of 20 g of water by 15 °C. Use the equation $Q = (4.18 \text{ J/g °C})m\Delta T$, where m is the mass and ΔT is the change in temperature. K/U

21. Ethanol, an excellent solvent for some biological molecules, is highly flammable. It has a boiling point of 78 °C. Suppose that a scientist is attempting to use hot ethanol to extract pigments from a small leaf. The scientist has a hot plate, a Bunsen burner, test tubes, beakers, test-tube clamps, a fume hood, and lab safety equipment. If the scientist wants to minimize the amount of ethanol used and perform the extraction in a test tube, what procedure and what protective equipment should be used? T/I

22. Outline a procedure that would be appropriate for each of the following tasks. K/U
    (a) testing for the presence of O_2 gas
    (b) testing for the presence of CO_2 gas
    (c) testing for the presence of starch
    (d) determining the pH of a solution

23. (a) What is the molar mass of each compound?
        (i) CH_3CH_2COOH
        (ii) $C_2H_5NH_2$
        (iii) $CH_3(CH_2)_8CH_3$
    (b) Draw a structural diagram for each compound.
    (c) Is each compound non-polar, polar, or ionic?
    (d) Is each compound acidic, basic, or neutral? T/I C

24. Which of the following processes are exothermic and which are endothermic? K/U T/I
    (a) a combustion reaction
    (b) the formation of snow and ice
    (c) the splitting of water into oxygen and hydrogen gas

CAREER PATHWAYS **PREVIEW**

Throughout this unit you will see Career Links. Go to the Nelson Science website to find information about careers related to metabolic processes. On the Chapter Summary page at the end of each chapter you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 3

An Introduction to Metabolism

KEY CONCEPTS

After completing this chapter you will be able to

- explain how potential energy is stored in chemical compounds and can be transferred and harnessed to carry out biological processes
- understand that the laws of thermodynamics govern the transfer of energy during all chemical and physical processes
- explain how free energy drives chemical reactions and couples endothermic reactions with exothermic reactions
- describe how the free energy released by the hydrolysis of ATP is used as the energy currency of the cell
- describe how enzymes influence the rate of a biochemical reaction by lowering the activation energy required to reach the transition state of the reaction
- explain how food contains stored chemical energy that can be released through controlled oxidation

How Is Energy Involved in Cellular Respiration?

All living things require energy. Hockey players need a great deal of energy to skate up and down the ice in pursuit of the moving puck. Power in their arms and back is necessary for shooting and passing. The twitching muscle fibres in their legs help players skate at high speeds, start and stop quickly, and reverse directions in a split second. Athletes of all types expend a lot of energy to perform well. Energy demands are not limited to sporting events. We need extra energy to sing, dance, play a musical instrument, or paddle a canoe. All body movement requires energy—from the movement of your eye muscles as you read this page, to the pumping of your blood through your blood vessels.

Energy is not just required for movement. The growth, maintenance, and repair of your body also require a constant supply of energy. You require energy even when you are sleeping. Simply thinking about what you are reading in this chapter requires energy. Although your brain is about 2 % of your body mass and does not have large moving parts, it uses about 20 % of the energy that is consumed by your body at rest.

Many plants and animals consume large amounts of energy. Consider Douglas fir trees, which can grow 0.5 m per year and reach a height of over 100 m. Some plants, such as the quaking aspen, can grow to immense proportions by propagating through their root system. Such growth requires an enormous amount of energy. In the animal world, cheetahs can run at a speed of 112 km/h. Humpback whales can be up to 15 m in length and weigh 48 tonnes, yet they can breach, or leap, with enough force to lift two-thirds of their body out of the water. Howler monkeys use energy to let loose a cry that can be heard up to 5 km away. Penguins in the Antarctic expend a great deal of energy to maintain an internal body temperature of between 35 °C and 42 °C, despite air temperatures below −50 °C.

What is energy, and how is it related to cellular processes? In this chapter, you will examine the concepts of metabolism, which will help you understand how energy flows during external physical activity and internal biological activity. You will learn how the energy stored in food ultimately came from the Sun. You will also learn how your body transforms the energy stored in different foods into a form it can use to carry out all the necessary movements and functions.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Energy is stored in the foods we eat. How is it transformed into usable energy in your body?
2. Food provides you with the energy needed to perform tasks such as climbing stairs and even thinking. Determining the amount of energy in food is quite challenging. Brainstorm to design a method you could use to compare the approximate amounts of energy in two or more samples of food.
3. All living things require energy. Some of the ways that energy is used are shared by all species, while other energy uses are specialized. For example, all organisms use energy for DNA synthesis, whereas only a few species, such as electric eels, use energy to generate a large electric shock.
   (a) Make a list of five energy uses that you believe are shared by many species.
   (b) Make a list of five specialized energy uses, and give examples of species that employ them.

Mini Investigation

Energy and Forces of Attraction

Skills: Predicting, Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1**

In a chemical reaction, the making and breaking of bonds lead to a change in energy. In this activity you will model energy changes that occur during chemical reactions by using magnets to represent atomic nuclei and steel balls to represent electrons.

Equipment and Materials: small steel ball (such as a ball bearing); weak magnet; strong magnet

1. Place the steel ball on a table. Slowly slide the weak magnet toward the ball until the ball "jumps" to the magnet.
2. Pull the ball away from the magnet.
3. Repeat Steps 1 and 2 using the strong magnet.
4. Bring the ball into contact with the strong magnet, and place them on the table.
5. Slowly slide the weak magnet directly toward the ball from the side opposite the strong magnet. Allow the weak magnet to touch the ball. Then, while holding on to the strong magnet, pull the weak magnet away from the ball.
6. Separate the ball from the strong magnet.
7. Attach the ball to the weak magnet, and place them on the table.
8. While holding on to the weak magnet, slide the strong magnet directly toward the ball from the side opposite the weak magnet. Observe how the ball reacts to the attraction of the strong magnet.
9. Pull the strong magnet away.

A. Which action, in Step 1 or Step 2, required the addition of energy from you? Which action released energy? T/I

B. When did the ball have the most energy? T/I

C. Which magnet has a stronger force of attraction to the ball? T/I

D. In Step 5, when the ball was bound to the strong magnet and the weak magnet was brought into contact with the ball, was there a release of energy? Did the ball move from one magnet to another? T/I

E. In Steps 6 and 7, you transferred the ball from the strong magnet to the weak magnet. Did the ball release energy, or did you add energy to make the ball move? T/I

F. In Steps 8 and 9 when the ball was bound to the weak magnet, you brought the strong magnet close to the ball. What happened to the ball as the strong magnet approached it? Was there a release of energy? Explain. T/I

G. Scientists describe electrons in weak bonds as having more potential energy than electrons in strong bonds. Use the model you have created to explain this reasoning. A

3.1 Metabolism and Energy

Figure 1 Japanese macaques, often called snow monkeys, expend a significant amount of energy to keep warm in their snowy environment. They forage for food to supply this energy.

All plants, animals, fungi, protists, and prokaryotes are in a constant struggle for survival. Throughout their life, organisms grow, protect themselves from danger, and reproduce. All of these processes require energy. Mammals and birds, which are endothermic, also need energy to maintain elevated body temperatures (**Figure 1**). Living organisms must continually capture, store, and use energy to perform this multitude of functions. Both prokaryotic and eukaryotic cells use ATP molecules to supply energy for their cellular work. In eukaryotic cells, most of the ATP is produced by mitochondria.

You can think of cells as microscopic chemical factories. For life processes to occur, thousands of chemical reactions take place within these microscopic factories. In some of the chemical reactions, large molecules (polymers such as DNA) are built from small molecules (monomers such as nucleotides). In other chemical reactions, polymers (such as amylose) undergo hydrolysis into monomers (such as glucose). The sum of these processes within an organism is called its **metabolism.**

metabolism the sum of all chemical reactions in a cell or organism

Energy—The Ability to Do Work

Work is performed when energy is used to move an object against an opposing force, such as friction or gravity. For example, it takes energy for a car to travel along a highway, and it takes energy for a mountain climber to climb a steep slope. These are observable physical activities that require energy. On a much smaller scale, it also takes energy to link amino acids into a chain to form a protein, or to pump sucrose across a cell membrane.

There are many forms of energy, including chemical, electrical, mechanical, light, and thermal. Energy is defined as the capacity to do work. Each form of energy can be converted to other forms of energy. In a battery, for example, chemical energy is converted to electrical energy. In a flashlight bulb, this electrical energy is converted to light and thermal energy. In nature, during the process of photosynthesis, light energy from the Sun is converted to chemical energy (stored in sugar) by organisms. Most living organisms obtain energy in one of two ways: by obtaining it directly from the Sun through photosynthesis, or by consuming energy-rich molecules within food webs that began with photosynthesis.

Kinetic Energy and Potential Energy

kinetic energy the energy of motion

potential energy the stored energy that an object possesses as a result of its position relative to other objects or to its internal structure

All energy exists in one of two states. **Kinetic energy** occurs as a result of motion. Waves in the ocean, falling rocks, molecules and ions moving in a solution, or heart muscles contracting with every heartbeat are examples of kinetic energy. The kinetic energy that is present in movement is useful because it can perform work by making other objects move.

Potential energy is stored within an object and is dependent on the object's location or chemical structure. Chemical potential energy is stored in the electrons and protons that make up atoms and molecules. The electrons are often involved in chemical bonds. A bond results when electrons are simultaneously experiencing a force of attraction to protons in the nuclei of two atoms. Chemical potential energy is available and can be released or absorbed during a chemical reaction. It is stored in food molecules such as glucose. When food molecules are broken down, usable energy is released to power the functioning of cells in an organism—to do cellular work.

Figure 2 This cyclist has gravitational potential energy as a result of his location at the top of the hill.

Another type of potential energy is gravitational potential energy. For example, a cyclist perched at the top of a hill has potential energy as a result of the high elevation (**Figure 2**). The gravitational pull of Earth at the high elevation is what gives the cyclist the potential energy. Similarly, a diver about to dive from a platform also has potential energy due to the force of gravity from Earth and her height above the surface of the water. The diver gains potential energy as her muscles work to climb the ladder and reach the top of the platform. When work is done, energy is transferred from one body or place to another. When she dives from the platform, the diver's speed increases and she gains kinetic energy. She also loses potential energy as the distance between her and the water surface decreases (**Figure 3**). Therefore, as the diver plunges toward the water, some of her potential energy is converted to kinetic energy.

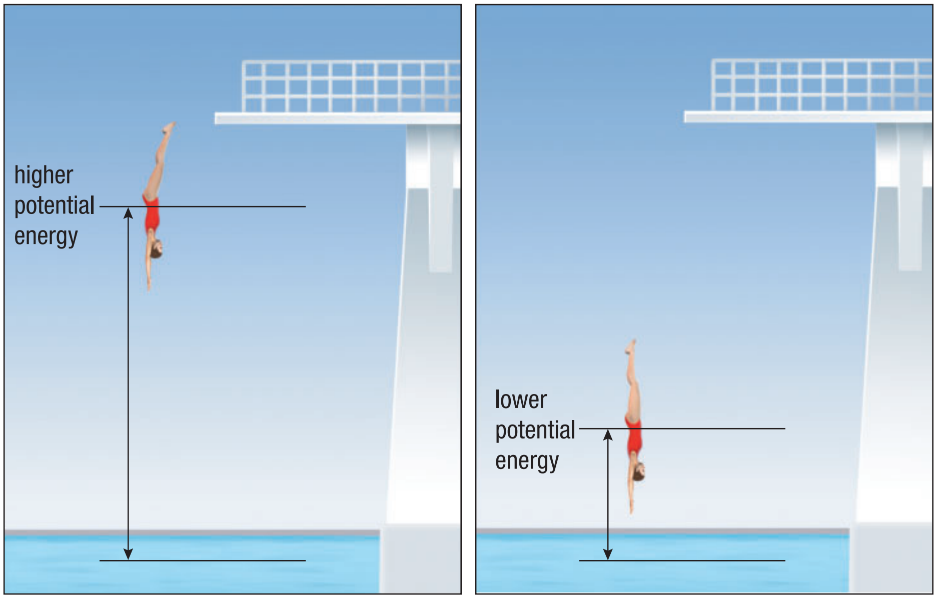


Figure 3 As the diver falls, her gravitational potential energy decreases.

The First Law of Thermodynamics

The diver example illustrates a fundamental law of nature known as the **first law of thermodynamics**: energy in the universe can be converted and transformed from one form to another, but energy cannot be created or destroyed—the total energy remains constant. This is also known as the law of energy conservation.

first law of thermodynamics principle that states that energy can be transferred or transformed, but it cannot be created or destroyed

The First Law of Thermodynamics

The total amount of energy in any closed system is constant. Energy cannot be created or destroyed; it can only be converted from one form to another. If a physical system gains an amount of energy, another physical system must experience a loss of energy of the same amount.

By converting sunlight into chemical energy, green plants act as energy transformers. During photosynthesis, plants capture light energy from the Sun. The plants then convert some of the light energy into chemical potential energy. The potential energy is stored in plant cells in the form of carbohydrates and other energy-rich molecules. The energy in these molecules is stored or is passed on to other organisms that rely on plants as a food source. In this manner, chemical energy is passed from plants to other organisms. Living organisms then convert the chemical energy into other forms of energy. For example, when woodland caribou living in northern Ontario consume plant material, chemical energy from the plants can later be converted to mechanical energy, which is used to contract muscles for movement (**Figure 4**). The caribou use this mechanical energy to move.

Figure 4 Caribou convert chemical energy from the food they eat into other forms of energy.

Energy and Chemical Bonds

Conversion of energy from one form into another depends on the breaking and forming of chemical bonds in a chemical reaction. During a chemical reaction, the amount of potential energy that is available changes. In the earlier example of the diver, the amount of potential energy was directly related to the height of the diver above the water. The higher the elevation, the greater the potential energy of the diver. In a similar way, the potential energy of electrons depends on their location with respect to positively charged atomic nuclei. Like the diver, the farther away electrons are from the nucleus of an atom, the more potential energy they have. The potential energy of outer electrons increases when they absorb energy, move farther from the nucleus, and reach an "excited" state. However, unlike the diver being pulled by Earth's gravitational force, there is not just one source of attraction; there are many sources, from many different atomic nuclei. These nuclei may vary in their forces of attraction. When electrons are strongly attracted to two nuclei at the same time, the resulting forces are called a chemical bond.

Energy Changes during a Chemical Reaction

During a chemical reaction, some of the bonds between atoms in the reactant molecules must be broken, and new bonds form between atoms in the product molecules. For bonds to break in the reactant molecules, energy must be absorbed because energy is required to pull an electron away from an atom. When bonds are formed between the atoms of product molecules, energy is released. Just as the diver loses potential energy as she gets closer to Earth, an electron loses potential energy as it gets closer to a nucleus. When methane, CH_4, burns, for example, all the bonds in the methane and oxygen molecules are broken as energy is absorbed (**Figure 5**). New bonds then form between carbon and oxygen atoms to make carbon dioxide, CO_2, and between hydrogen and oxygen atoms to make water, H_2O. As these products form, energy is released. Thus, the reaction involves both the absorbing and releasing of energy.

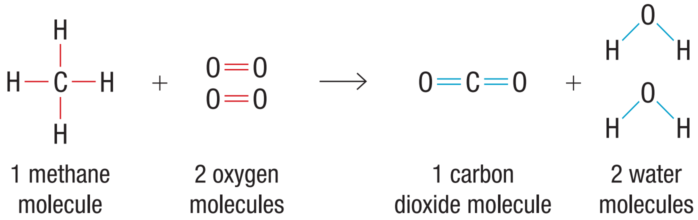


Figure 5 The combustion of methane gas. Bonds broken are shown in red; bonds formed are shown in blue.

As bonds break and new bonds form, the positions of some electrons in the atoms change. The change in potential energy of these electrons accounts for the change in energy during a chemical reaction. To break a bond, electrons must be pulled away from the nucleus of an atom. This action of pulling away always requires energy but at the same time increases the electrons' potential energy. Therefore, the breaking of bonds always requires additional energy. However, when electrons form a new bond, they move closer to the nucleus of another atom and release energy (like the diver falling down toward Earth). The released energy can be converted to different forms, including thermal, light, vibrational, or mechanical energy. For example, the light and thermal energy that comes from the flame of a burning candle is the result of electrons involved in bond formation.

Bond Energy

Bond energy is a measure of the strength or stability of a covalent bond. It is measured in units of kilojoules per mole (kJ/mol) and is equal to the amount of energy absorbed per mole when the bond between atoms is broken. A **mole** is a standard quantity equal to approximately 6.022×10^{23}. This value, also called Avogadro's number, is used in chemistry when considering numbers of extremely small particles. The bond energy value is equal to the amount of energy released per mole when the same bonds form. The energy needed to break a bond reflects the relative strength of the bond. For example, if it takes 799 kJ/mol to break a double bond between carbon and oxygen (C=O), this bond is roughly twice as strong as the C–H bond (411 kJ/mol). Therefore, roughly twice as much energy is released when C=O bonds form.

bond energy the minimum amount of energy that is required to break a particular type of bond; measured in kJ/mol of bonds

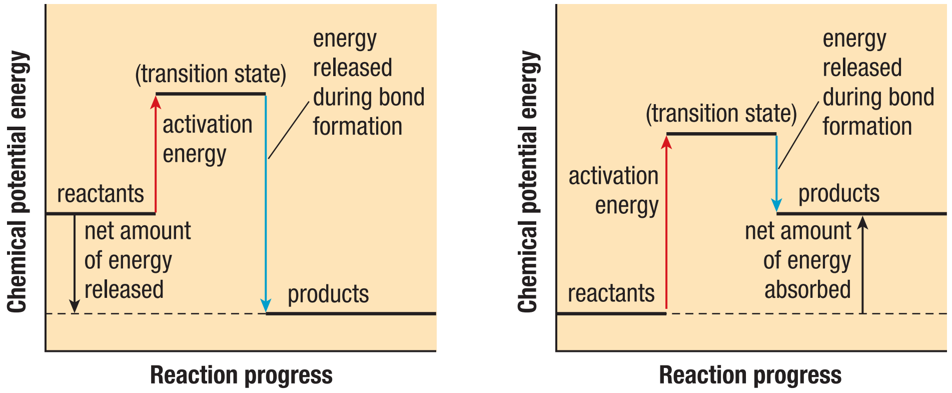
mole the number (approximately 6.022×10^{23}) of atoms or molecules whose mass in grams is equal to the atomic mass of one such particle in atomic mass units; one carbon atom has a mass of 12 AU, and, therefore, one mole of carbon atoms has a mass of 12 g

Table 1 lists the average bond energies of the most common types of chemical bonds found in biological molecules. The values are averages because actual bond energies vary depending on the other atoms in the molecules. For example, the bond energy of the O−H bond will vary depending on what other atoms the O forms a bond with.

All chemical reactions involve the absorption of energy as bonds break in the reactants and the release of energy as bonds form in the products. Therefore, energy is always required to start a reaction, even if there is an overall release of energy in the chemical reaction. The **activation energy (E_a)** of a reaction is the minimum amount of energy needed to break bonds in the reactants and start the chemical reaction. For example, there must be a spark or a match to start a fire and the process of combustion. Although this may be a small amount of energy, it is enough to break the first bonds and initiate the chemical reaction. Once the reaction begins, it releases enough energy to break bonds in other reactant molecules and keep the process going.

The **transition state** of a chemical reaction is the temporary condition in which bonds in the reactants have reached their breaking point and new bonds are ready to form in the products. The activation energy of a reaction is equal to the difference between the potential energy of the reactants and the potential energy during the transition state (**Figure 6(a)**). As products are formed in a reaction, energy is always released. If the bonds that form in the products are stronger than the bonds in the reactants, the energy released as the bonds form will be greater than the energy absorbed as the bonds were broken. This type of reaction, in which there is a net release of energy, is an **exothermic reaction**. Figure 6(a) shows a potential energy diagram for an exothermic reaction. As you can see, the chemical potential energy of the products is less than the chemical potential energy of the reactants. Also, the energy released when forming the products is greater than the energy absorbed when breaking the bonds in the reactants.

In other reactions, the energy absorbed in breaking the bonds of the reactants may be greater than the energy released as new bonds are formed in the products. This results in a net absorption of energy. The reaction is called an **endothermic reaction**. **Figure 6(b)** shows a diagram of the energy changes during an endothermic reaction. Note that the potential energy of the products is greater than the potential energy of the reactants. This means that the activation energy required to break the bonds and start the reaction is greater than the energy released when products are formed.


Chemical potential energy
(transition state)
energy released during bond formation
activation energy
reactants
net amount of energy released
products
Reaction progress
Chemical potential energy
energy released during bond formation
(transition state)
activation energy
products
net amount of energy absorbed
reactants
Reaction progress

(a) exothermic reaction

(b) endothermic reaction

Figure 6 Changes in energy during (a) exothermic and (b) endothermic reactions: The activation energy that is required to initiate the reaction is represented by the red arrow. The energy that is released by the products forming is represented by the blue arrow. The overall energy change for the reaction is represented by the black arrow.

In the following tutorial, you will calculate the net energy change in simple exothermic and endothermic chemical reactions.

Table 1 Average Bond Energies

Bond type	Average bond energy (kJ/mol)
H−H	436
C−H	411
O−H	459
N−H	391
C−C	346
C−O	359
C=O	799
O=O	494

activation energy (E_a) the minimum amount of energy that chemical reactants must absorb to start a reaction

transition state a temporary condition during a chemical reaction in which the bonds in the reactants are breaking and the bonds in the products are forming

exothermic reaction a chemical reaction in which energy is released, leaving the products with less chemical potential energy than the reactants

endothermic reaction a chemical reaction in which energy is absorbed, giving the products more chemical potential energy than the reactants

LEARNING **TIP**

Calculating Molar Mass

The molar mass of a compound is the mass of one mole (6.022×10^{23} molecules) of the compound. This is the sum of all the molar masses of all the atoms in a molecule of the compound. For the compound NaCl, the molar mass (taken from the atomic mass shown in the periodic table) equals the mass of one mole of Na (23 g/mol) added to the mass of one mole of Cl (35.5 g/mol). Thus, the molar mass of NaCl is 58.5 g/mol.

Tutorial 1 Estimating Energy Changes during a Chemical Reaction

In this tutorial, you will calculate the energy changes that occur during simple reactions, such as the combustion of methane, the decomposition of water, and the reactions that occur when we consume energy-rich foods. By calculating the net change in energy in the chemical reaction between the reactants and the products, you will be able to determine whether a reaction is exothermic or endothermic.

Sample Problem 1: The Combustion of Methane

Determine the energy changes, per gram of methane, that occur during its complete combustion.

Step 1. Write and balance the chemical equation:

methane gas + oxygen gas → carbon dioxide gas + water

This equation can be written using the chemical formulas of each molecule:

$CH_4 + O_2 \rightarrow CO_2 + H_2O$

The chemical equation must be balanced so that there is the same number of each type of atom on both sides of the arrow. The balanced equation looks like this:

$CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O$

Step 2. Examine the bond arrangements of the reactants and the products.

During the combustion of methane gas, all of the original C–H and O=O bonds in the reactants are broken. You know this because there are no bonds of these types in the final products. Therefore, all the bonds in the products are newly formed during the reaction. To determine all the bonds that are in both the reactants and the products, it is helpful to draw the structure of each chemical (**Figure 7**).

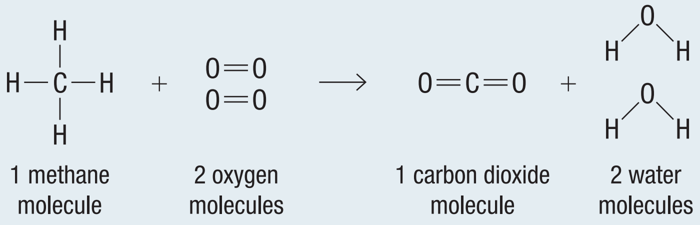


Figure 7 Structural diagram showing all the bonds in a methane combustion reaction

Step 3. Calculate the net energy change.

Use the bond energy values listed in Table 1 (page 129) to estimate the energy changes that occur when reactant bonds are broken and when product bonds are formed. At the start of the reaction, four C–H bonds and two O=O bonds are broken. Using Table 1, calculate the total energy absorbed by adding the energies required to break each bond as follows:

4(C–H bond energy) + 2(O=O bond energy) = total bond energy of 1 mol of methane and 2 mol of oxygen

4(411 kJ/mol) + 2(494 kJ/mol) = 2632 kJ absorbed during the breaking of reactant bonds

This is the energy that was required to pull apart all of the bonds in the reactants. However, during the reaction, six new bonds form: two C=O bonds and four H–O bonds. When these bonds form, energy is released. The amount of energy released is calculated as follows:

2(C=O bond energy) + 4(H–O bond energy) = total bond energy of 1 mol of carbon dioxide and 2 mol of water

2(799 kJ/mol) + 4(459 kJ/mol) = 3434 kJ released during the formation of product bonds

With these values, you can determine the net energy change for the combustion of methane. In this reaction, the energy released when bonds are formed is greater than the energy absorbed when bonds are broken. The net energy change is the difference between the energy released by bonds forming and the energy absorbed to break bonds, where BE is bond energy:

$\text{BE}_{\text{released}} - \text{BE}_{\text{absorbed}} = \text{net energy released by reaction}$

$3434\text{ kJ} - 2632\text{ kJ} = 802\text{ kJ}$

Based on the balanced equation, the value of 802 kJ represents the energy released by burning one mole of methane gas. Since methane has a mass of 16 g/mol, you can also express this energy value as

$$\frac{802\text{ kJ/mol methane}}{16\text{ g/mol}} = 50\text{ kJ/g of methane}$$

Since the overall value represents a net release of energy, you know that the combustion of methane gas is an exothermic reaction. The thermal energy released by the reaction can be used to heat our homes.

Sample Problem 2: The Decomposition of Water

Determine the net energy change that occurs during the decomposition of water into hydrogen and oxygen gas. Express your answer in units of kJ/g of water.

Step 1. Write and balance the chemical equation:

water → hydrogen gas + oxygen gas

This equation can be written using the chemical formulas of the molecules involved:

$H_2O \rightarrow H_2 + O_2$

The balanced chemical equation looks like this:

$2\,H_2O \rightarrow 2\,H_2 + O_2$

Step 2. Examine the bond arrangements of the reactants and the products.

Now that you know the chemical formulas for the reactants and products, look at the bond arrangements of each. **Figure 8** shows the structure of each molecule.

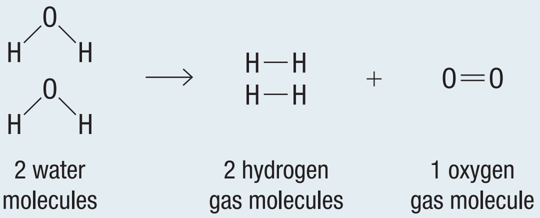


Figure 8 Structural diagram of the decomposition of water, with all the bonds shown

In the reactant, water, O–H bonds are broken. The bonds that form in the products are O=O bonds and H–H bonds. All of the bonds in the reactant are broken, and all of the bonds in the products are newly formed.

Step 3. Calculate the net energy change.

Use the bond energy values (Table 1, page 129) to estimate the energy changes that occur when bonds are broken and formed. You see that four O–H bonds in the reactants are broken.

Therefore, you can calculate the total energy absorbed by adding the energies required to break each bond as follows:

4(O–H bond energy) = total bond energy of 4 O–H bonds in 2 molecules of water

4(459 kJ/mol) = 1836 kJ absorbed in the breaking of reactant bonds

This is the energy required to pull apart the bonds in the reactant molecules. However, during the reaction, two H–H bonds and one O=O bond are formed. When these bonds form, energy is released. The amount of energy released is calculated as follows:

2(H–H bond energy) + 1(O=O bond energy) = total bond energy of 2 molecules of hydrogen and 1 molecule of oxygen

2(436 kJ/mol) + 1(494 kJ/mol) = 1366 kJ released during the formation of product bonds

In this reaction, the energy absorbed when breaking the O–H bonds in the reactants is greater than the energy released by the formation of bonds in the products. The net energy change is the difference between the energy released by bond formation and the energy absorbed by bond breakage, where BE is bond energy. For convenience, you can rearrange the equation to obtain a positive value for the energy absorbed during the reaction:

$BE_{absorbed} - BE_{released}$ = net energy absorbed by reaction

1836 kJ – 1366 kJ = 470 kJ

Based on the balanced equation, this is the energy required to decompose two moles of water. The mass of one mole of water is 18 g, so the mass of two moles is 36 g. Therefore, you can also express this energy value as

$$\frac{470\text{ kJ}}{36\text{ g}} = 13\text{ kJ/g of water}$$

In the decomposition of water molecules, energy must be provided from an outside source. This reaction is not a source of energy (like burning methane in Sample Problem 1), but rather an energy consumer. Therefore, you know that the decomposition of water is an endothermic reaction.

Investigation 3.1.1

The Energy Content of Foods (p. 156)
In Investigation 3.1.1, you will perform a quantitive analysis to determine the energy content of various types of food.

Sample Problem 3: The Energy Content of Food

Determine the net energy change that occurs during the complete oxidation of the simple fatty acid, butanoic acid (C_3H_7COOH). You will estimate the energy change that occurs when this food molecule is completely oxidized. Assume that the complete oxidation of any compound containing carbon, hydrogen, and oxygen atoms will result in the formation of carbon dioxide and water. CAREER LINK

Step 1. Write and balance the chemical equation.

The basic chemical reaction is as follows:

butanoic acid + oxygen gas → carbon dioxide gas + water

Rewrite the equation using the chemical formulas of the molecules involved:

$C_3H_7COOH + O_2 \rightarrow CO_2 + H_2O$

The balanced equation for this reaction is as follows:

$C_3H_7COOH + 5\ O_2 \rightarrow 4\ CO_2 + 4\ H_2O$

Step 2. Examine the bond arrangements of the reactants and the products.

Use the diagram to determine the numbers and kinds of bonds that are broken and formed. Assume that all the bonds in the reactants are broken and all the bonds in the products are newly formed.

The structure of each molecule is shown in **Figure 9**.

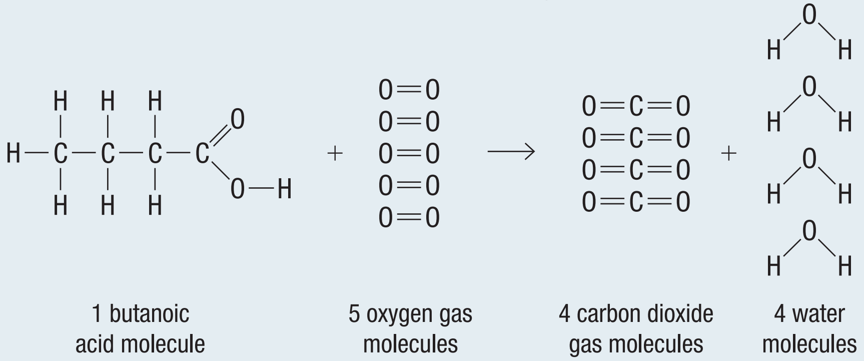


Figure 9 Structural diagram of the reaction for the oxidation of butanoic acid. All bonds are shown.

Step 3. Calculate the net energy change.

The bonds in the reactants that are broken are three C–C bonds, seven C–H bonds, one C=O bond, one C–O bond, one O–H bond, and five O=O bonds. Using the values from Table 1 (page 129), calculate the total energy absorbed by adding the energies required to break each bond as follows:

$$3(346 \text{ kJ/mol}) + 7(411 \text{ kJ/mol}) + 799 \text{ kJ/mol} + 359 \text{ kJ/mol} + 459 \text{ kJ/mol} + 5(494 \text{ kJ/mol}) = 8002 \text{ kJ absorbed during the breaking of reactant bonds}$$

The bonds that are formed in the products are eight C=O bonds and eight O–H bonds. When these bonds are formed, energy is released. The amount of energy released is calculated as follows:

$$8(799 \text{ kJ/mol}) + 8(459 \text{ kJ/mol}) = 10\,064 \text{ kJ released during the formation of product bonds}$$

Therefore, the energy released by the formation of bonds in the products is greater than the energy added by breaking the bonds in the reactants. The energy released is

$$10\,064 \text{ kJ} - 8002 \text{ kJ} = 2062 \text{ kJ}$$

One mole of butanoic acid has a mass of 88 g/mol, so the energy content per gram is

$$\frac{2062 \text{ kJ/mol}}{88 \text{ g/mol}} = 23 \text{ kJ/g of butanoic acid}$$

The overall oxidation reaction releases energy; therefore, the oxidation of butanoic acid is an exothermic reaction.

Practice

1. Calculate the energy released per gram of propane when it is burned in a combustion reaction. The chemical formula for propane is C_3H_8 (**Figure 10**). T/I [ans: 46 kJ/g]
2. Calculate the energy released by the burning, or oxidation, of 1 g of glucose, $C_6H_{12}O_6$ (**Figure 11**). T/I [ans: 15 kJ/g]

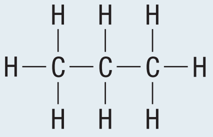


Figure 10 Chemical structure of propane

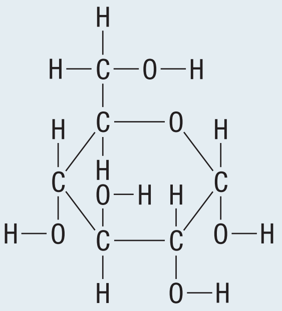


Figure 11 Chemical structure of glucose

3. Compare the energy released, per gram, during the complete combustion of butanoic acid (Sample Problem 2) with the energy released during the complete combustion of methane (Sample Problem 1). Which substance has more potential energy? Explain to a classmate how you came to your conclusion. T/I C

The Second Law of Thermodynamics

second law of thermodynamics principle that states that every time energy is converted to another form, some of the energy becomes unusable

If energy is neither created nor destroyed, why do organisms have to keep replenishing their energy supply? According to the **second law of thermodynamics**, in every energy transfer or conversion, some of the useful energy in the system becomes unusable; that is, it is unavailable to do work. The unusable energy is usually in the form of thermal energy, which is the energy associated with random molecular motion. This is one reason why machines are never 100 % efficient. For example, the engine of a car converts only about 25 % of the potential energy in gasoline into the kinetic energy that makes the car move. Likewise, only a portion of the energy in a laptop computer battery is used to run the computer. If you touch a car engine or laptop computer that has been in use, it is obvious that the remaining energy is being lost to the surroundings as thermal energy. This concept of energy efficiency also applies to living cells. As you will see in Chapter 4, through the process of cellular respiration, cells are able to convert about 40 % of the potential energy in glucose into a form usable for metabolism; the remainder is lost as thermal energy. In many cases, including in living cells, this thermal energy cannot be harnessed to do work; instead, it is simply lost to the environment (**Figure 12**).

Figure 12 A runner converts only 40 % of the energy from glucose into a useful form. Most of the energy is unused and given off as thermal energy in the form of body heat.

The Second Law of Thermodynamics

In every energy transfer or conversion, some of the useful energy in the system becomes unusable and increases the entropy of the universe.

entropy a measurement of disorder in a system

Whether referring to a car or to the cells of a living organism, the release of unusable energy, in the form of random particle motion during an energy transformation, leads to an increase in the disorder, or randomness, of the system. In the field of thermodynamics, the degree of disorder is a measurable quantity called **entropy**. The total entropy of a system and its surroundings increases whenever there is any change, such as a chemical reaction. Therefore, all systems in the universe tend toward disorder. Disorder increases when an orderly arrangement of objects becomes more randomly assorted. For example, no matter how much energy you may expend to tidy up your room, it always gets messy again.

At the level of chemical and physical changes, an increase in entropy is usually associated with a breaking down of large particles into smaller particles, or the spreading out of particles. When ice melts, a large crystal structure is broken down into countless individual molecules. When liquid water evaporates, the water molecules that were in close contact as a liquid spread out over large distances. Likewise, when a substance in solution diffuses from an area of higher concentration to an area of lower concentration, its molecules become more randomly distributed, corresponding to an increase in entropy. In chemical reactions, entropy increases when

- solids react to form liquids or gases
- liquids react to form gaseous products
- the total number of product molecules is greater than the total number of reactant molecules

One characteristic of all living things is that they are highly ordered structures. A flower, the compound eye of an insect, and the human brain are all very highly ordered structures (**Figure 13**). Living cells have the ability to create order from a disordered arrangement. For example, individual nucleotide molecules link together to synthesize DNA, a highly ordered macromolecular structure. Proteins are very ordered structures constructed from many small amino acid building blocks.

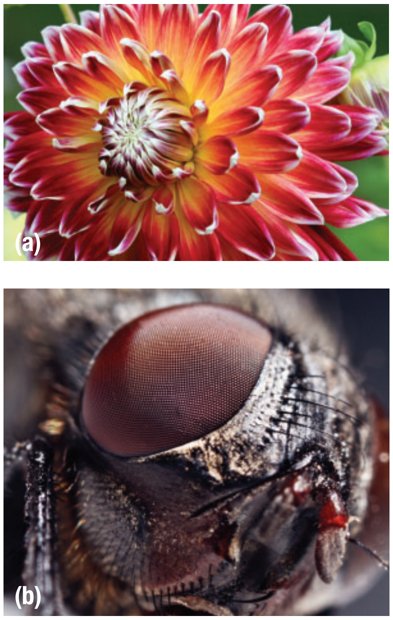


Figure 13 (a) A flower and (b) the compound eye of an insect, such as this fly, are highly ordered structures.

These examples may seem to suggest that living organisms do not follow the second law of thermodynamics. This is *not* true. Just as you can expend energy to tidy your room when it becomes disorderly, living cells can, by expending energy, establish and maintain complex and orderly structures and processes. In other words, it is possible to maintain a level of low entropy in a system; however, it requires energy. This energy may be in the form of chemical potential energy in a sandwich (**Figure 14**) or in photons of light absorbed by a green plant. Living things bring in energy and matter and use them to establish order out of disorder. It is understandable why elite athletes need to eat a lot of energy-rich food, but even people who do not have a high energy demand for movement need to ingest enough food to supply energy, simply to maintain their cells in a highly ordered state.

According to the second law of thermodynamics, the overall entropy of the system always increases. The thousands of chemical reactions that take place to maintain order in a living system release energy in the form of thermal energy and the by-products of metabolism, such as carbon dioxide. These by-products and released energy increase the entropy of the surroundings, but the living organisms themselves maintain order. Therefore, entropy of the organism decreases, but the overall entropy of the universe increases.

Figure 14 The average person needs to ingest between 9000 and 12 000 kJ per day. A significant amount of this energy is used to maintain the order within our cells. We eat food to maintain low entropy.

Spontaneous Changes

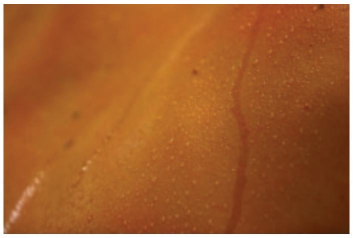
The first and second laws of thermodynamics allow us to predict whether a given chemical or physical change can occur without the continuous input of additional energy. A **spontaneous change** is one that will continue to occur on its own once it is underway. Unlike in everyday language where the word "spontaneous" means that some event can and will happen on its own, in thermodynamics, spontaneous means only that a change will continue to happen on its own once it is underway. For example, a match will not suddenly burst into flame. However, once a match is lit, it will continue to burn on its own without any continual addition of energy. Therefore, the burning of a match is classified as a spontaneous change. Similarly, a diver high on a diving board will not begin his dive until he jumps—but once he jumps, his falling motion will continue on its own. Therefore, we say that diving into a swimming pool is a spontaneous change.

spontaneous change a change that will, once begun, continue on its own under a given set of conditions; does not require a continuous supply of energy

A non-spontaneous reaction cannot occur without a continual input of energy. For example, if you heat a pot of water until it starts boiling and then take it off the heat source, the water will not continue to boil. Under normal conditions, you would describe the boiling of water as a non-spontaneous change. The water will only boil if there is a continuous addition of energy. To revisit the messy room analogy, you could describe the change from a tidy room to a messy room as a spontaneous change because it can happen "on its own." However, a change from a messy room to a tidy room is not spontaneous; it will only occur when there is a continual supply of energy—from you!

Physical changes that are thermodynamically spontaneous may occur at various rates—ice will melt quite slowly at 1 °C but will melt much more rapidly at 50 °C. Spontaneous chemical change may also be very slow, as when rust forms on a nail, or very fast, as when a match burns. To determine whether a change will occur spontaneously, you must take three factors into account: energy changes, entropy, and temperature (**Table 2**, next page). Exothermic changes that are accompanied by an increase in entropy occur spontaneously, since both the change in energy (energy is released during the change) and the change in entropy (increase) are favourable. A favourable change means that it does not require an additional supply of energy. Energy is needed for endothermic changes and for changes that increase order (decrease entropy). Endothermic changes accompanied by a decrease in entropy do not occur spontaneously; neither the change in energy (the overall change requires an addition of energy) nor the change in entropy (an increase in order requires an addition of energy) is favoured. In changes in which the energy change is exothermic (favoured) and the entropy decreases (not favoured), and in changes in which the energy change is endothermic (not favoured) but entropy increases (favoured), the spontaneity of the changes depends on the temperature at which they occur.

Table 2 Factors Influencing Spontaneous and Non-spontaneous Changes

	Exothermic change (favoured)	Endothermic change (not favoured)
Increase in entropy (favoured)	spontaneous at all temperatures example: wood burning	spontaneous at high temperatures; not spontaneous at low temperatures  example: sweat evaporating from the surface of the skin
Decrease in entropy (not favoured)	spontaneous at low temperatures; not spontaneous at high temperatures example: water freezing	not spontaneous at any temperature; requires a continuous input of energy to proceed example: glucose being synthesized during photosynthesis

Gibbs Free Energy

free energy energy that can do useful work; also called Gibbs free energy

According to the second law of thermodynamics, energy transformations are never 100 % efficient. Some energy is always lost to the environment, which leads to an increase in entropy. The energy that is not lost, or the portion that is still available to do work in the given system, is called **free energy**. The free energy value of a chemical reaction provides us with useful information in the study of metabolism. Free energy values tell us which types of reactions provide fuel to our bodies—fuel that releases the energy needed for cellular work. Free energy is represented by the symbol *G*, in recognition of the physicist who developed the concept, Josiah Willard Gibbs.

The concept of free energy applies to both chemical and physical processes. Therefore, free energy may be released during a chemical reaction or during a physical act, such as water spilling over a waterfall. In fact, all processes in our universe require a source of free energy. However, at the completion of a process, there is a reduction in the amount of free energy that is available in a given system.

In living organisms, free energy is responsible for the chemical and physical work required in activities such as the synthesis of molecules, reproduction, and movement. The change in free energy (ΔG) can be represented by the following equation:

$$\Delta G = G_{\text{final state}} - G_{\text{initial state}}$$

The value of ΔG can be calculated for any chemical reaction. We can use bond energy changes to quantify the total amount of energy released from a reaction, but we know, from the second law of thermodynamics, that some of this energy is lost and therefore unavailable to do work. For example, when an organism oxidizes one mole of butanoic acid, it releases approximately 470 kJ of energy. However, not all of this energy is free energy that is available to do work. Processes in the cell can only use a portion of the energy, and the rest is released as thermal energy.

The change in free energy (ΔG) represents the difference in the free energy of the final state of molecules as compared to the free energy of the initial state. Therefore, a negative ΔG value indicates that the free energy of the products of a reaction is less than the free energy of the reactants. The energy released during a reaction with a negative ΔG can be used to do work in other reactions that require energy. Conversely, a positive ΔG value indicates that the products have more free energy than the reactants. These products must have obtained free energy from an external source. A reaction with a negative ΔG gives off free energy, which is then available to do work. A reaction with a positive ΔG must gain free energy to occur. Free energy must be supplied for this type of reaction to happen—it cannot happen on its own. Therefore, reactions with a negative ΔG occur spontaneously, and reactions with a positive ΔG do not (**Figure 15**).

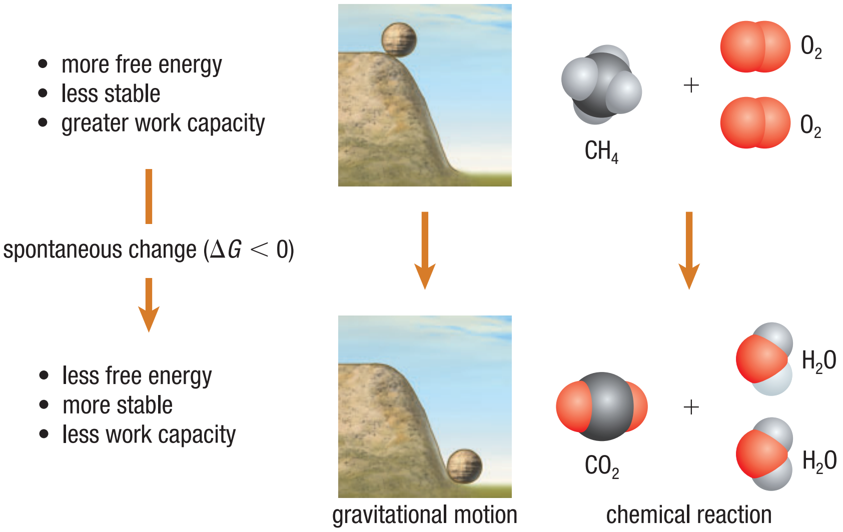


Figure 15 This diagram shows the relationship between free energy, stability, and work capacity. Unstable systems (top) have a high value of free energy and a greater capacity to do work because they have a higher potential energy. They can spontaneously change into the more stable system (bottom) with less free energy. The free energy that was released could have been used to do work.

The oxidation of glucose is an example of a reaction that releases free energy:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \quad \Delta G = -2870 \text{ kJ/mol of glucose oxidized}$$

The negative ΔG value indicates that the reaction is spontaneous. Free energy is released during the reaction, so the products have less free energy than the reactants. There is also an increase in entropy because there are more molecules of the products than molecules of the reactants.

Plants combine CO_2 and H_2O to create sugars through the process of photosynthesis. This reaction is the opposite of glucose oxidation and is an example of a chemical reaction that has a positive ΔG value:

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2 \quad \Delta G = +2870 \text{ kJ/mol of glucose formed}$$

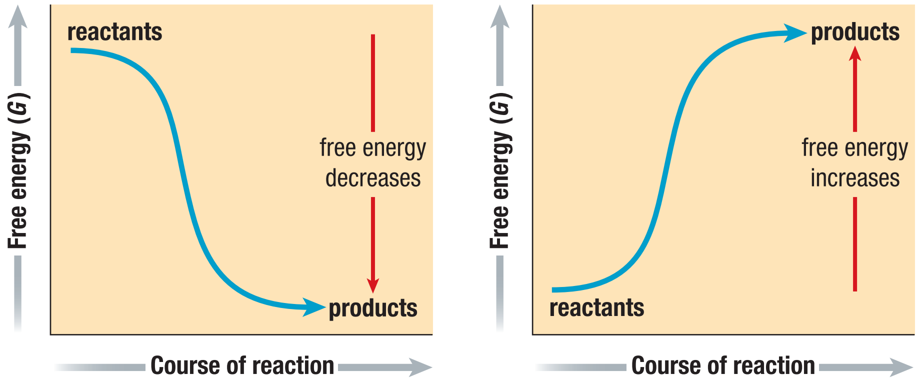
The positive ΔG value indicates that the reaction is not spontaneous—it must gain free energy to occur. Keep in mind that a process resulting in an increase in free energy can never occur spontaneously. In this particular reaction, plant cells are able to use light to supply free energy and make the reaction proceed.

Every reaction falls into one of two groups, based on the free energy of the reactants and the products. An **exergonic reaction** releases free energy. The ΔG value is negative in this type of reaction because the products contain less free energy than the reactants (**Figure 16(a)**, next page). Exergonic reactions can do work because they act as a source of free energy. Releasing free energy gives cells the ability to do work—to move, to grow, and to reproduce. An example of an exergonic reaction is the burning

exergonic reaction a chemical reaction that releases free energy; the products have less free energy than the reactants of wood. A major component of wood is cellulose, which is a large carbohydrate composed of linked glucose molecules. We can think of these glucose molecules, along with oxygen gas molecules, as the reactants in the process that contain a lot of potential energy. Burning the wood releases free energy from these glucose molecules.

endergonic reaction a chemical reaction that absorbs free energy; the products have more free energy than the reactants

The second type of reaction is an **endergonic reaction**, in which the products contain more free energy than the reactants (**Figure 16(b)**). The Δ*G* value for these reactions is positive, and the reactants in an endergonic reaction must absorb free energy from the surroundings to transform into the products. An example of an endergonic reaction is the conversion of carbon dioxide and water into glucose and oxygen gas. This reaction requires an input of free energy.



(a) exergonic reaction

(b) endergonic reaction

Figure 16 (a) In an exergonic reaction, free energy is released. The products have less free energy than was present in the reactants, and the reaction proceeds spontaneously. (b) In an endergonic reaction, free energy is gained. The products have more free energy than was present in the reactants. An endergonic reaction is not spontaneous: it proceeds only if energy is supplied by an exergonic reaction.

Coupled Reactions

energy coupling the transfer of energy from one reaction to another in order to drive the second reaction

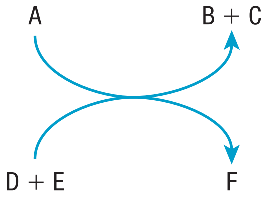
Every type of cell in every organism continuously carries out thousands of exergonic and endergonic reactions. Exergonic reactions release free energy and therefore can proceed spontaneously. Endergonic reactions require a supply of free energy and therefore cannot proceed on their own. Cells are able to make endergonic reactions happen by supplying them with the free energy released by an exergonic reaction. In other words, cells couple exergonic reactions to endergonic reactions. This is called **energy coupling**. For example, consider the following generic chemical reactions:

$$\mathrm{A} \rightarrow \mathrm{B} + \mathrm{C} \quad \Delta G = -5\ \mathrm{kJ/mol}$$

During this exergonic reaction, 5 kJ of free energy is released from the overall reaction. A second endergonic reaction requires the addition of 4 kJ of free energy:

$$\mathrm{D} + \mathrm{E} \rightarrow \mathrm{F} \quad \Delta G = +4\ \mathrm{kJ/mol}$$

The energy required by reactants D and E to produce F can be supplied by the first exergonic reaction. We say that the first reaction is coupled to the second reaction (**Figure 17**).



$$\mathrm{A} \rightarrow \mathrm{B} + \mathrm{C} \qquad \Delta G = -5\ \mathrm{kJ/mol}$$

$$\underline{\mathrm{D} + \mathrm{E} \rightarrow \mathrm{F} \qquad \Delta G = +4\ \mathrm{kJ/mol}}$$

$$\text{Coupled reactions:} \quad \mathrm{A} + \mathrm{D} + \mathrm{E} \rightarrow \mathrm{B} + \mathrm{C} + \mathrm{F} \qquad \Delta G = -1\ \mathrm{kJ/mol}$$

Figure 17 An exergonic reaction can be coupled to an endergonic reaction to provide free energy.

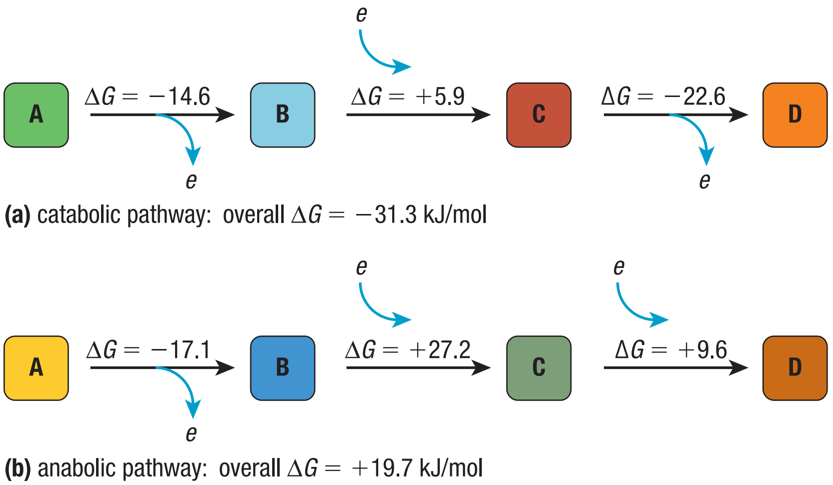
When combined, the coupled reactions have a net negative Δ*G*. Free energy is released and both reactions, when coupled, can occur spontaneously. For an endergonic reaction to proceed, it must be coupled with an exergonic reaction that releases more free energy than the endergonic reaction requires. In cells, all endergonic reactions are coupled to such exergonic reactions.

The sum of all individual reactions is an organism's metabolism. In metabolism, individual reactions tend to be part of a metabolic pathway, which is a series of sequential reactions in which products of one reaction are used immediately as reactants for the next reaction in the series. In a **catabolic pathway**, complex molecules are broken down into simpler compounds, thereby releasing free energy. An example of a catabolic pathway is cellular respiration, in which energy is extracted from the breakdown of food such as glucose. This is discussed in detail in Chapter 4. In contrast, an **anabolic pathway** (often called a biosynthetic pathway) consumes free energy to build complicated molecules from simpler molecules. Examples of anabolic pathways include photosynthesis, which is covered in Chapter 5, and the synthesis of macromolecules such as proteins and nucleic acids.

catabolic pathway a pathway in which energy is released and complex molecules are broken down into simple molecules

anabolic pathway a pathway in which energy is supplied to build complex molecules from simple molecules

The overall Δ*G* of an anabolic pathway is positive, whereas the overall Δ*G* of a catabolic pathway is negative. However, any one pathway may be made up of a number of individual chemical reactions. Some of these reactions may not have the same sign (positive or negative) for Δ*G* as the overall pathway (**Figure 18**). Regardless of the overall Δ*G* value for an entire pathway, each endergonic step can proceed only if it is coupled with an exergonic reaction.



(a) catabolic pathway: overall $\Delta G = -31.3$ kJ/mol

(b) anabolic pathway: overall $\Delta G = +19.7$ kJ/mol

Figure 18 Examples of a catabolic pathway and an anabolic pathway: (a) The catabolic pathway has three steps. Free energy is released in the first and last steps and added in the middle step. The middle step is endergonic and must be coupled with an exergonic reaction (not shown). The overall change in free energy from A to D is negative. (b) The anabolic pathway also has three steps, but the overall change in free energy is positive. While the first step is exergonic, releasing energy and proceeding spontaneously, the next two steps are endergonic and must be coupled with exergonic reactions to supply the needed free energy.

All living things perform numerous activities that result in an increase in the free energy (+Δ*G*) of the products or substances involved—they move, grow, repair and reproduce. These activities need a continuous supply of free energy. Cells need a constant, convenient source to provide this free energy. As you are about to learn, free energy is usually supplied by the energy carrier molecule ATP.

3.1 Review

Summary

- Energy is the ability to do work. All living things require a constant supply of energy.
- The first law of thermodynamics states that energy transforms from one form to another or transfers from one object to another, but it is neither created nor destroyed.
- During a chemical reaction, bonds in the reactants break and bonds in the products form. For the bonds in the reactants to break, energy must be absorbed. As bonds form, energy is released.
- The second law of thermodynamics states that in every transfer and conversion of energy, there is less energy available to do work. The total entropy of a system and its surroundings always increases.
- Gibbs free energy (G) is the energy in a system that is still available to do work after a reaction occurs.
- Exergonic reactions have a negative ΔG value, are spontaneous, and release free energy.
- Endergonic reactions have a positive ΔG value, are not spontaneous, and absorb free energy. They must be coupled with an exergonic reaction to proceed.
- Metabolic pathways are a series of chemical reactions. Catabolic pathways result in an overall decrease in free energy—free energy is released. Anabolic pathways result in an overall increase in free energy—free energy is absorbed.

Questions

1. Explain the relationship between the terms in each pair:
   (a) energy and work
   (b) potential energy and kinetic energy
   (c) free energy and spontaneous changes K/U
2. Describe the relationship between bond energy and energy changes that occur during a chemical reaction. K/U
3. (a) Calculate the overall energy change in the combustion of ethane, C_2H_6. Is it an exothermic reaction or an endothermic reaction?
   (b) Compare the energy released per gram from ethane with the energy released from glucose and butanoic acid. (See Tutorial, page 132.)
   (c) Based on these examples, predict which compounds contain more energy per gram: hydrocarbons, fats, or carbohydrates. K/U T/I
4. If the activation energy of a reaction is 1250 kJ/mol, and the energy released by the formation of products in the reaction is 1386 kJ/mol, what type of reaction has taken place? T/I
5. Explain how organisms can grow and create internal order without violating the second law of thermodynamics. K/U T/I
6. Is the releasing of light by a firefly endergonic or exergonic? Explain how such a process abides by the first and second laws of thermodynamics. K/U
7. In your own words, describe the difference between anabolic and catabolic pathways. K/U C
8. For each of the following, state whether the event or process is spontaneous or non-spontaneous, and under what conditions you would expect it to occur. T/I
   (a) Organic food waste decomposes.
   (b) A bacterial cell propels itself through water using a flagellum.
   (c) Honey bees perform a hydrolysis reaction to convert sucrose into a mixture of glucose and fructose.
   (d) Electric eels generate powerful electric fields to stun their prey and to defend themselves.
9. (a) Describe the first and second laws of thermodynamics.
   (b) Explain why some people might mistakenly think that living things do not obey the second law. K/U
10. Which of the following processes are spontaneous? Give an example of each spontaneous process. K/U T/I A
    (a) an exothermic process that increases entropy in a setting with a low temperature
    (b) an exothermic process that decreases entropy in a setting with a high temperature
    (c) an endothermic process that increases entropy in a setting with a high temperature
    (d) an endothermic process that decreases entropy in a setting with a low temperature

ATP: Energy Currency of the Cell

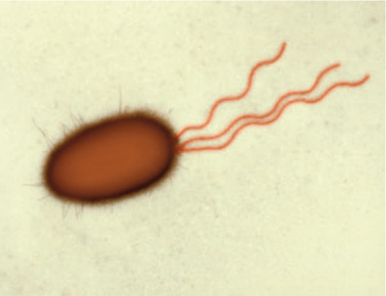


Figure 1 A bacterium with flagella

Thousands of reactions take place in living cells. Many reactions require the addition of energy for the assembly of complex molecules from simple reactants. These reactions include DNA synthesis, protein synthesis, and the construction of cell walls and other cellular structures. Other cell-driven actions—such as muscle contractions in animals, the motion of flagella in bacteria (**Figure 1**), and the movement of sap within a tree—also require a supply of energy.

Since so many cellular functions require energy, cells need a constant supply of energy. Even though the species on Earth are very diverse, all cells in every organism use the same energy carrier for almost all of their energy-driven actions. This energy comes in the form of a compound called adenosine triphosphate, or ATP. ATP directly supplies the energy that powers nearly every cellular function, and it is considered the universal energy "currency." The types of work that are carried out by ATP include mechanical, transport, and chemical work (**Table 1**).

Table 1 Types of Work Performed by ATP

Mechanical work	Transport work	Chemical work
• beating of cilia or movement of flagella • contraction of muscle fibres • movement of chromosomes during mitosis/meiosis	• process of pumping substances across membranes against their concentration gradient	• process of supplying chemical potential energy for non-spontaneous, endergonic reactions, including protein synthesis and DNA replication

ATP Hydrolysis and Free Energy

Adenosine triphosphate (ATP) consists of three parts: a nitrogenous base called adenine, which is linked to a five-carbon sugar called ribose, which in turn is linked to a chain of three phosphate groups (**Figure 2**, next page). ATP contains large amounts of free energy. The energy of the molecule is high because of its three negatively charged phosphate groups. The phosphate groups crowd together, and their close proximity creates a mutual repulsion of their electrons. The mutual repulsion contributes to the weakness of the bond holding the groups together. The bonds of ATP are easily broken by a catalyzed reaction with water—a process called hydrolysis (Figure 2). The hydrolysis reaction results in the breaking off of the end (or terminal) phosphate group and the formation of two products—adenosine diphosphate (ADP) and an inorganic phosphate (P_i). In addition, an H^+ ion is released into the solution. As bonds in these new products form, free energy is released.

$$\mathrm{ATP} + \mathrm{H_2O} \rightarrow \mathrm{ADP} + \mathrm{P_i} \quad \Delta G = -30.5 \text{ kJ/mol}$$

Note that the H^+ ion is not normally shown in the chemical equation, since it is understood to be associated with the formation of P_i.

Recall, from Section 3.1, that during a chemical reaction, bonds in the reactants break and new bonds in the products form. During ATP hydrolysis, bonds form when a new —OH group attaches to the phosphorus atom of the phosphate group and when an electron attaches to the oxygen that remains on the ADP molecule. Energy is also released as the H^+ ion interacts with water molecules. The bond rearrangements and the change in entropy result in an overall free energy change of –30.5 kJ/mol. When ATP splits into ADP and P_i within a cell, the phosphate group, rather than remaining free in solution, often becomes attached to another molecule, which results in a different bonding arrangement.

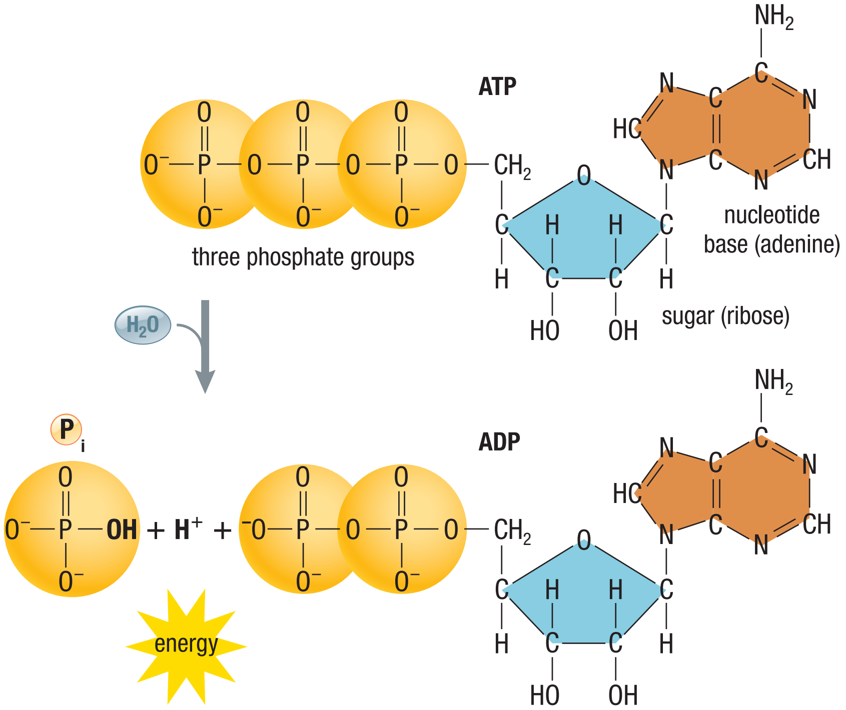


Figure 2 ATP releases large amounts of free energy during a hydrolysis reaction as new bonds form in the products. The reaction results in the addition of a new OH group to a released phosphate as well as the addition of an electron to the terminal oxygen on the ADP and the release of an H^+ ion into solution.

ATP and Energy Coupling

phosphorylation the transfer of a phosphate group, usually from ATP, to another molecule

In a process called energy coupling (Section 3.1), ATP can be moved into close contact with a reactant molecule of an endergonic reaction. Then, during the reaction, the terminal phosphate group breaks away from the ATP and transfers to the reactant molecule. Attaching a phosphate group to another organic molecule is a process called **phosphorylation**. It results in the molecule gaining free energy and becoming more reactive. Energy coupling requires an enzyme to bring the ATP molecule close to the reactant molecule of the endergonic reaction. There are specific sites on the enzyme that bind both the ATP molecule and the reactant molecule. In this way, the two molecules are brought close to one another, and the transfer of the phosphate group takes place.

Most of the work carried out in a cell is dependent on phosphorylation for energy. An example of energy coupling that is common to most cells is the reaction in which ammonia, NH_3, is added to glutamic acid (**Figure 3(a)**, next page). The resulting product of this reaction is glutamine, which is an amino acid. The reaction can be written as follows:

$$\text{glutamic acid} + \text{ammonia} \rightarrow \text{glutamine} + H_2O \quad \Delta G = +14.2 \text{ kJ/mol}$$

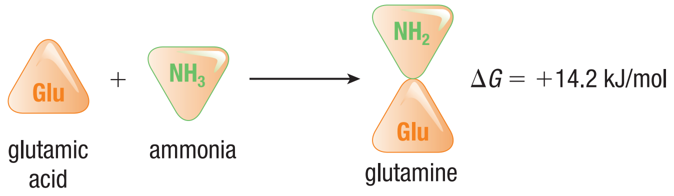
The glutamine that is produced takes part in the assembly of proteins during protein synthesis. The positive value of ΔG shows that the reaction is endergonic and cannot proceed spontaneously. Therefore, the coupling of this reaction with ATP hydrolysis gives it the necessary energy to proceed. As a first step, the phosphate group is removed from the ATP and transferred to the glutamic acid molecule, forming glutamyl phosphate (**Figure 3(b)**, next page):

$$\text{glutamic acid} + \text{ATP} \rightarrow \text{glutamyl phosphate} + \text{ADP} \quad \Delta G < 0$$

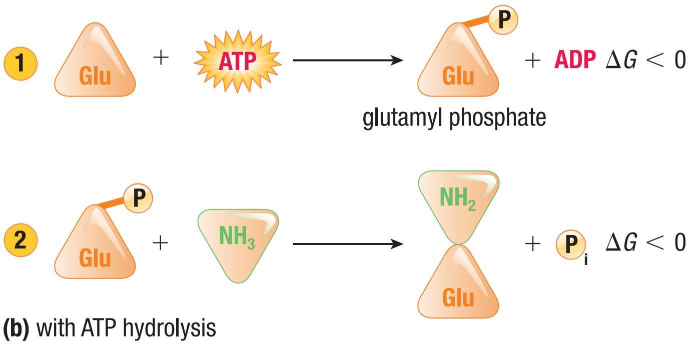
The change in free energy, ΔG, is negative for this reaction. This means that the reaction is exergonic and can proceed spontaneously. In the second step of the reaction, glutamyl phosphate reacts with ammonia:

$$\text{glutamyl phosphate} + \text{ammonia} \rightarrow \text{glutamine} + P_i \text{ (inorganic phosphate)} \quad \Delta G < 0$$

The second step of this reaction also has a negative ΔG value, so it also proceeds spontaneously. The overall ΔG value for the two-step reaction is -16.3 kJ/mol (**Figure 3(c)**). This example represents a two-step endergonic reaction that is coupled to ATP hydrolysis, but there are hundreds, thousands, or even millions of steps involved in the assembly of huge protein molecules or the synthesis of an entire DNA genome. The process is analogous to building a huge wall, one brick at a time. This step-by-step approach is what enables cells to perform these large tasks. ATP molecules provide energy every step of the way.



(a) without ATP



(b) with ATP hydrolysis

$$\begin{array}{rcll} \text{Glu} + \text{NH}_3 & \longrightarrow & \text{Glu} - \text{NH}_2 & \Delta G = +14.2 \text{ kJ/mol} \\ \text{ATP} & \longrightarrow & \text{ADP} + \text{P}_i & \underline{\Delta G = -30.5 \text{ kJ/mol}} \\ & & & \text{net } \Delta G = -16.3 \text{ kJ/mol} \end{array}$$

(c) free energy change with ATP

Figure 3 Energy coupling using ATP: (a) Ammonia is added to glutamic acid to form glutamine. This is a non-spontaneous, endergonic reaction. (b) In the presence of ATP, a phosphate is transferred to glutamic acid. This forms glutamyl phosphate, which spontaneously reacts with ammonia to form glutamine. (c) ATP provides the free energy for the overall reaction and allows it to occur spontaneously.

Regeneration of ATP

For cells to keep functioning, they must regenerate ATP molecules. In the previous section, you learned how the hydrolysis of ATP into ADP and inorganic phosphate, P_i, is an exergonic reaction that can be coupled with endergonic reactions to drive them forward spontaneously. ATP coupling reactions occur continuously in living cells and, consequently, an enormous number of ATP reactions are required.

Cells generate ATP by combining ADP with P_i. If ATP hydrolysis is an exergonic reaction, then the reverse process, ATP synthesis from ADP and P_i, is an endergonic reaction. Therefore, ATP synthesis requires the addition of free energy. The energy needed to drive ATP synthesis usually comes from the exergonic breakdown of complex molecules containing an abundance of free energy. These complex molecules are in the foods we eat: carbohydrates, fats, and proteins. All of these molecules are sources of free energy. In Chapter 5, you will learn that light energy is also a primary source of energy used to drive ATP synthesis. At least 10 million times every second, ATP molecules are hydrolyzed and resynthesized in a typical cell, illustrating that this

ATP cycle the cyclic and ongoing breakdown and re-synthesis of ATP

cycle operates at an astonishing rate. In fact, if ATP were not formed in the cell from ADP and P_i, the average human would need about 75 kg of ATP per day. The continued breakdown and resynthesis of ATP is a process called the **ATP cycle** (**Figure 4**).

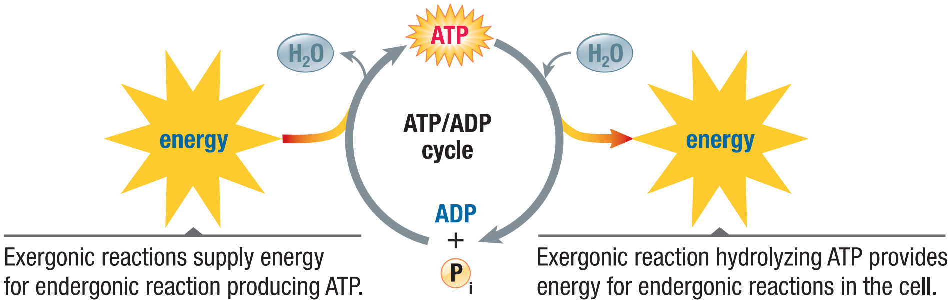

ATP
H_2O
H_2O
energy
ATP/ADP cycle
energy
ADP
+
P_i
Exergonic reactions supply energy for endergonic reaction producing ATP.
Exergonic reaction hydrolyzing ATP provides energy for endergonic reactions in the cell.

Figure 4 The ATP cycle couples reactions that release free energy (exergonic) to reactions that require free energy (endergonic).

ATP Is the Universal Energy Currency

There is very little ATP in our diet, and yet we require it as a constant energy source within our cells. ATP hydrolysis releases energy obtained from the foods we eat, and then more energy from food is used to reassemble the ATP. If cells constantly need to use energy from food to reassemble ATP, then why do cells use ATP as their energy currency to begin with? It would seem that cells could just use the food molecules directly as sources of energy. Cells use ATP as an immediate source of energy because it has specific properties that are important for the biochemical reactions that allow proper cell functioning.

ATP provides a manageable amount of energy, and couples in very similar ways to thousands of different reactions in our cells. This ability to couple to so many different endergonic reactions gives ATP its "universal" characteristic. The widespread use of ATP in all living things is an evolved characteristic. Many other molecules are energy rich, but they vary in size and shape, in the amount of energy they release, and in the types of reactions to which they can couple. Also, the availability of these molecules is not always reliable or predictable. If a certain reaction required the use of a particular food molecule—for example, glucose—as an energy source to drive a coupled reaction, and the cell did not have any glucose, it could not power the given reaction, even if there were other energy-rich molecules in the cell. The ability to assemble ATP using the energy from a variety of food molecules ensures that all vital reactions in the cell can be performed. Complex food molecules also require numerous reactions to release their energy, but ATP can be created and accessed immediately. The only requirement is that at least one of these food sources is available for generating ATP. Although ATP is the energy currency of cells and is the immediate source of energy to drive cellular processes, it is not the only energy carrier in cells. There are other phosphate carriers, such as guanosine triphosphate (GTP), that are used specifically as carriers of high-energy electrons.

In this section, you learned that cells can use ATP as a source of energy to drive endergonic reactions. There are, however, other factors that influence a cell's ability to perform endergonic and even exergonic reactions. Critical among these factors is the need to overcome the activation energy requirements for a particular reaction (Section 3.1). If the activation energy requirement is very high because the bonds in the reactants are very strong, a reaction will not start even if it is exergonic overall. As you will learn in the next section, some proteins called enzymes play an important role in lowering the activation energy for certain reactions.

3.2 Review

Summary

- ATP supplies energy directly to chemical reactions in all cells. It is the universal energy currency in living organisms.
- ATP hydrolysis results in the formation of ADP and P_i, and releases a large amount of free energy in the process.
- ATP hydrolysis can be coupled to endergonic reactions in a cell to power hundreds of reactions. This process is called energy coupling.
- Phosphorylation, the process of attaching a phosphate group to another organic molecule, causes the molecule to gain free energy and become more reactive.
- ATP is regenerated from ADP and P_i during part of the ATP cycle.

Questions

1. Provide an example of a use of ATP energy for each of the following tasks:
   (a) chemical work
   (b) mechanical work
   (c) transport work K/U
2. What does the universality of ATP in all living species suggest about the relationship of species to one another? A
3. (a) Describe the structure of an ATP molecule.
   (b) How does the structure of the ATP molecule relate to the large amounts of free energy it contains? K/U
4. Describe the process of ATP hydrolysis. K/U
5. During the hydrolysis of ATP, energy is released, but most of the molecule, the ADP portion, remains intact. How does this compare to what happens to a molecule of glucose when it is used as an energy source? T/I
6. With a classmate, explain the relationship between the ATP cycle and the coupling of exergonic and endergonic reactions. K/U C
7. Which of the following groups of molecules has more overall free energy? Explain your answer. K/U
   - Group 1: glutamic acid, NH_3, and ATP
   - Group 2: glutamine, ADP, and P_i
8. Why is it necessary for cells to "recycle" ADP and P_i rather than just release them as waste products? K/U
9. Use a flow chart or another graphic organizer to explain the ATP cycle. K/U C
10. Describe a phosphorylation reaction. K/U
11. Examine the following set of reactions: T/I
    (i) $A + B \rightarrow C$ $\Delta G = +4.4$ kJ/mol
    (ii) $D \rightarrow E + F$ $\Delta G = -3.0$ kJ/mol
    (iii) $M + N \rightarrow P + R$ $\Delta G = -6.2$ kJ/mol
    (iv) $S + T \rightarrow V$ $\Delta G = +2.1$ kJ/mol
    (a) Which of these reactions are spontaneous?
    (b) List all combinations of two reactions that would result in an overall spontaneous reaction.
12. Explain why it is advantageous for cells to use ATP as an energy source rather than using glucose, lipids, or protein directly. K/U
13. An unusual form of biological work is the production of light. Conduct research online to determine how fireflies use ATP energy to produce their well-known flashes of light (**Figure 5**). How efficient is this process? T/I

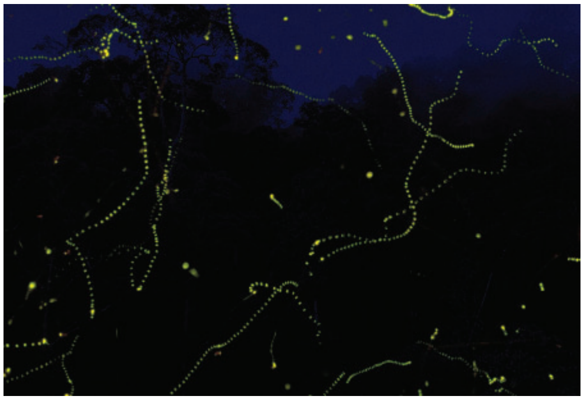


Figure 5

WEB LINK

3.3

Enzymes and Activation Energy

There is often more than one way to get from point A to point B. Imagine that you are riding a bicycle along a route from one location to another, and you must bike up and over a very high and steep hill. Rather than attempting to generate the energy to make it over the top of the hill, suppose that you could take an alternative route with a much lower hill. You would reach the same destination, but you would not have had to overcome such an energy-demanding obstacle. Enzymes do for chemical reactions what this alternative route does for your bicycle trip. Enzymes do not affect where a reaction "begins" or "ends," and they do not supply energy, but they do influence energy changes along the way. Enzymes enable chemical reactions to proceed more readily by reducing the amount of activation energy that the reactants must overcome—enzymes lower the energy "hills" in chemical reactions.

Without the addition of enzymes to cellular reactions, metabolism in living organisms would be very slow. The laws of thermodynamics help us determine whether a reaction will proceed with or without the addition of energy, but not how rapidly it will occur. Information about the energy changes for the overall reaction can help us predict whether a given chemical reaction is spontaneous or non-spontaneous. For example, using the laws of thermodynamics, we can calculate that the ΔG of the breakdown of sucrose into glucose and fructose is −31 kJ/mol. This indicates that the reaction releases free energy and can proceed without an outside source of energy. However, a solution of sucrose can sit for years without ever breaking down into glucose and fructose. This is an important point worth repeating: just because a reaction *can* proceed on its own does not mean that it *will* proceed. This section focuses on how the speed at which a reaction occurs can be increased by enzymes.

Enzymes as Catalysts

As you learned in Unit 1, enzymes are biological catalysts that are almost always proteins. Recent research has revealed that some RNA molecules can also function as enzymes. A Canadian scientist, Maud Menten, was among the first scientists to shed light on the fundamental role of enzymes (**Figure 1**). She developed a mathematical equation to measure the rates of enzyme reactions and explained the basis of enzyme kinetics. Enzymes combine briefly with reactant molecules, speed up the rate of a reaction, and are then released unchanged. The only function of the enzyme catalyst in a reaction is to lower the potential energy level of the transition state; thus, more reactants reach the transition state at a faster rate, and products form more quickly. The catalyst does not alter the physical composition of the products of a reaction in any way.

Figure 1 Maud Menten

Each enzyme has one or more binding sites that bind to a specific type of reactant substrate. Once a substrate binds, the enzyme-substrate complex catalyzes the given chemical reaction. These catalyzed reactions are reversible and are often written with the name of the enzyme above the reaction arrow:

$$\text{maltose} + \text{water} \xrightarrow{\text{maltase}} \text{glucose} + \text{glucose}$$

In the reaction above, the enzyme maltase catalyzes the hydrolysis of maltose to produce two glucose molecules. Notice that you can often recognize an enzyme and the substrate, or the reaction it catalyzes, by its name. The root of its name is often based on the substrate, and it usually ends in the suffix *–ase*. Thus, the enzyme *maltase* catalyzes a reaction involving maltose. Other names indicate the type of reaction that the enzymes catalyze. For example, enzymes that remove carboxyl functional groups from larger molecules are called decarboxylases.

Activation Energy as a Barrier to Chemical Reactions

The breakdown of sucrose into fructose and glucose is a spontaneous reaction, but it does not proceed quickly. Remember that during a typical chemical reaction, the bonds of the reactants must break before the bonds of the products can form. In Section 3.1, you learned that all reactions possess an activation energy (E_a) barrier that must be overcome for the reaction to move forward. Activation energy is that boost of energy required to break the initial bonds in the reactants. For the initial bonds to break with the addition of activation energy, reactant molecules must be in the correct geometric orientation, and they must collide with enough force for their bonds to break. It is under these conditions of added energy that the transition state of the reaction is reached. The transition state must be reached before new bonds and new products can form. Therefore, even though a reaction may be spontaneous (negative ΔG), as in the breakdown of sucrose, the reaction will not actually start until the needed activation energy is gained by the reactants (**Figure 2(a)**).

A rock sitting in a depression at the top of a hill is a physical example of the requirement of activation energy to get a process started (**Figure 2(b)**). The rock is blocked from rolling down the hill by the barrier, even though, from its position at the top of the hill, it has a considerable amount of potential energy and rolling down the hill would be a spontaneous action. The overall process also has a negative ΔG value, which confirms that it is a spontaneous process. In the example, activation energy is analogous to the energy required to push the rock up over the barrier so it can start rolling downhill.

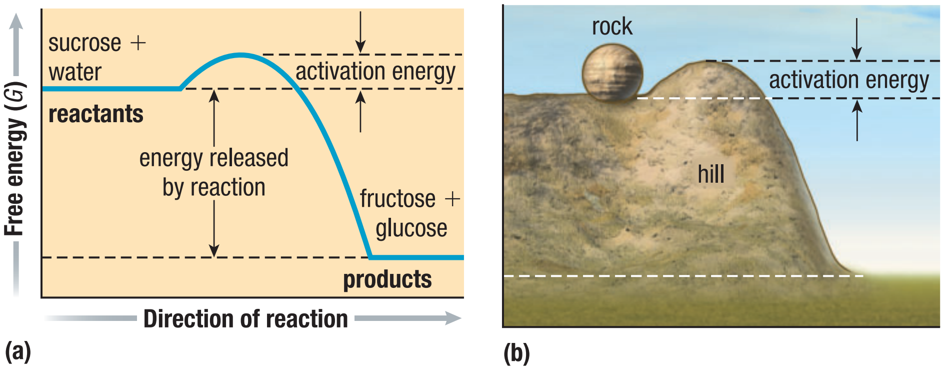


Figure 2 (a) Sucrose molecules must overcome the activation energy barrier for the reaction to proceed and for glucose and fructose to form. (b) An analogous physical process: a rock poised in a depression atop a hill must overcome a barrier with the addition of energy (activation energy) before starting to roll down the hill.

What provides the activation energy for a chemical reaction? The molecules that are involved in any given reaction are in constant motion. Sometimes these molecules may possess enough energy from their movement to reach the transition state of the reaction. In most cases, thermal energy is the source of activation energy in a reaction. For example, propane is a molecule that has a great deal of free energy; therefore, it spontaneously reacts with oxygen to form carbon dioxide and water. However, a spark of energy is needed to break some initial bonds within the mixture of reacting propane and oxygen molecules (**Figure 3**). The spark creates a region of very high temperature, with molecules moving at high speeds and with a great deal of kinetic energy. This increase in kinetic energy is enough to cause some bonds to break when the molecules collide. With the initial thermal energy and enough bonds broken, new bonds begin to form in the products CO_2 and H_2O. The formation of these bonds releases a great deal more thermal energy, which can be used to break more bonds in more propane and oxygen molecules, causing the reaction to continue.

Figure 3 The combustion of propane is a spontaneous reaction that must overcome an activation barrier to proceed. A small spark gives a sufficient amount of energy to some reactants to overcome the activation barrier and reach the transition state.

An increase in temperature is one way to speed up a chemical reaction. However, high temperatures are problematic in biology for two reasons. First, high temperatures can destroy the structural components of some proteins and DNA so that they lose their ability to function. This can lead to cell death. Second, an increase in the thermal energy of the particles in a cell would not be a good way of achieving activation energy in reactions because it would speed up *all* the reactions in the cell, not just one specific reaction. The progress of each chemical reaction in a cell must be regulated independently. Specific chemical reactions need to start and stop at given times or in specific situations. Therefore, even though thermal energy is a great source of activation energy for some chemical reactions, living cells need a more specialized way of controlling chemical reactions.

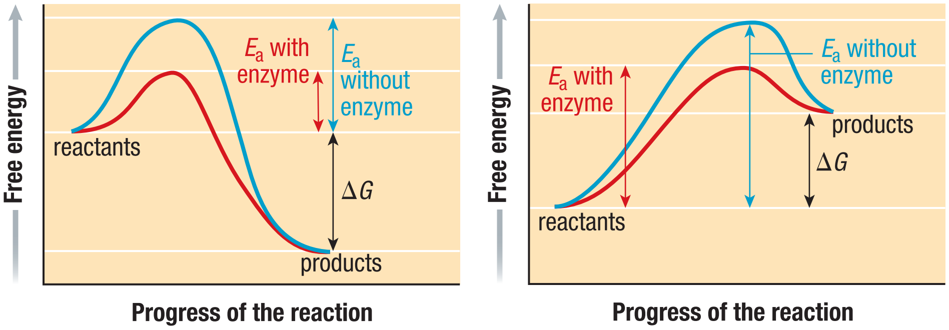
Lowering Activation Energy with Enzymes

Rather than an increase in temperature, cells use enzymes to speed up chemical reactions. These enzymes remain unchanged at the end of a reaction and speed up but do not change the chemical makeup of the products that are formed in the reaction.

Enzymes increase the rate of a reaction by lowering the activation energy of the reaction, thereby lowering the energy barrier **(Figure 4)**. (In the bike-riding example in the introduction, the height of the hill represents this energy barrier.) The rate of the reaction is proportional to the number of reactant molecules that can overcome the activation barrier to reach the transition state. When the enzymes lower the activation energy barrier, more reactant molecules can reach the transition state at a faster rate. Because the enzyme does not alter the reactants or the products, the change in free energy, ΔG, of the reaction—the difference between the free energy of the products and the free energy of the reactants—is unaffected by the enzyme. The only change is the path taken by the reaction. The effect of enzymes on exergonic and endergonic reactions is illustrated in Figure 4 (a) and (b). **Table 1** summarizes some of the characteristics of enzymes.

Table 1 Characteristics of Enzymes

Enzymes DO	• lower the activation energy of a reaction • increase the rate of a spontaneous (exergonic) reaction
Enzymes DO NOT	• alter the products of a reaction • supply free energy (ΔG) to a reaction • make an endergonic reaction proceed spontaneously



(a) exergonic reaction **(b)** endergonic reaction

Figure 4 Enzymes lower the activation energy of both (a) exergonic reactions and (b) endergonic reactions. Enzymes do not affect the ΔG of a reaction.

One question left to answer is how enzymes actually reduce the activation energy of a reaction. You must first understand that substrate molecules need to be in the transition state for a reaction to proceed. Enzymes function as a catalyst and increase the number of reactant molecules that reach the transition state. They are able to do this in three different ways. First, enzymes may bring the molecules together (**Figure 5(a)**, next page). Substrate molecules need to collide with each other to reach the transition state. When both substrate molecules bind to the enzyme, they are in an ideal proximity and orientation for catalysis to occur.

In a second mechanism, enzymes expose the reactant molecules to altered charged environments that promote catalysis (**Figure 5(b)**, next page). The active site of some enzymes contains ionic groups with positive or negative charges that attract and/or repel parts of the substrate. This stresses bonds in a way that favours catalysis.

In a third mechanism, enzymes can change the shape of the substrate (**Figure 5(c)**). The active site of the enzyme can strain or distort the substrate molecule, which weakens its chemical bonds. This reduces the amount of energy required to break the bonds. This mechanism of enzyme-substrate interaction is called the induced-fit model.

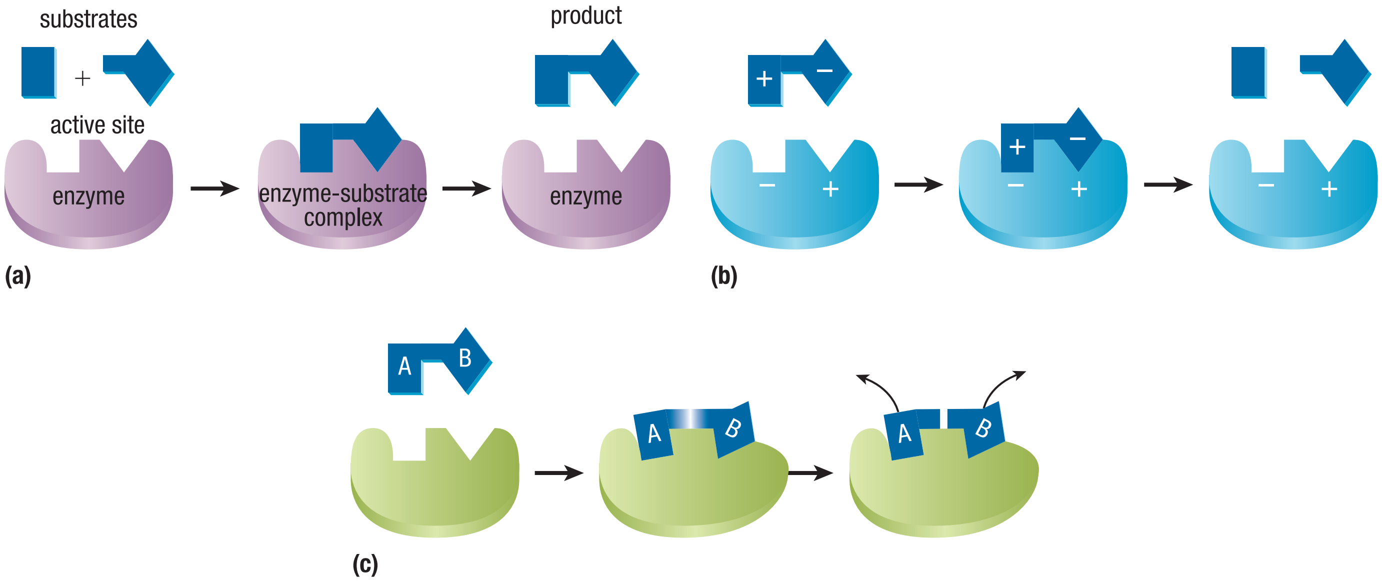


Figure 5 (a) Enzymes can bring both substrates into contact by binding them to specific sites. This allows them to collide more easily so that bonds can be broken more quickly and new bonds can form. (b) Enzymes can bring a substrate into a charged environment and alter the substrate. (c) Enzymes can distort or bend the shape of a substrate, which weakens the chemical bonds.

The specific shape of an enzyme creates its binding sites and allows it to function properly. If an enzyme is heated or chemically altered, it undergoes a process called denaturation and loses its shape. Misshapen enzymes cannot function effectively. The temperature range in which enzymes retain their shape is tuned to the specific reactions they are specialized to assist.

In all three enzyme mechanisms, the substrate molecule (or molecules) binds to the active site, which results in the substrate reaching the transition state. Substrates may be able to acquire the transition state without enzymes; however, under the conditions that exist within cells, most reactions would proceed extremely slowly, if at all.

UNIT TASK **BOOKMARK**

Consider what you learn in this Research This as you select an application for the Unit Task on page 252.

Research This

Using Enzymes in Bioremediation and Waste Treatment

Skills: Researching, Analyzing, Communicating

SKILLS HANDBOOK **A4.1**

There are many practical applications for enzymes. Among these is the use of enzymes to help preserve our environment. In this activity, you will research the use of enzymes in bioremediation or waste treatment. CAREER LINK

1. Choose one application of an enzyme used to protect the environment, either bioremediation or waste treatment, and research how enzymes play a role in the process.

A. How are enzymes used in the process? T/I

B. What is the source of enzymes commonly used in the process? Are they in their natural state, or have they been modified? T/I

C. Use a t-chart to list the advantages and disadvantages of using enzymes in this application. T/I C

D. Some enzymes can be used to convert organic waste materials, such as wood, into biofuel. Brainstorm possible advantages and disadvantages of this enzyme application. T/I

WEB LINK

3.3 Review

Summary

- An activation energy barrier must be overcome for any reaction to proceed. Activation energy initiates the breaking of bonds in reactants as they reach the transition state.
- The spontaneity of a reaction does not predict how fast it will occur. Some spontaneous reactions are very slow.
- Enzymes speed up reactions by lowering the activation energy of the reaction.
- Enzymes can bring reactants to the transition state by one of three mechanisms: bringing the two reactants closer together, changing the charged environment around the substrate, or bending or distorting the substrate.
- Enzymes are used in many industrial processes.

Questions

1. In this section, you briefly learned about the Canadian scientist Maud Menten. Research her scientific career, and explain in more detail how she contributed to the study of enzyme kinetics. T/I C
2. Many spontaneous reactions occur very slowly. If they can occur, why do all spontaneous reactions not take place immediately? K/U
3. Some enzymes are ingredients in cleaning solutions for contact lenses. They catalyze the breakdown of proteins that can accumulate on the surface of a lens. Suggest a possible name for this type of enzyme. K/U
4. Draw and label a graph to illustrate the effects of an enzyme on the activation energy of an exergonic reaction and an endergonic reaction. Refer to your graphs to explain why the addition of an enzyme will not change the ΔG of either type of reaction. K/U C
5. Examine the graphs in **Figure 6**, depicting reaction pathways. Which of these two reactions would benefit the most by the addition of an enzyme? Explain your reasoning. T/I

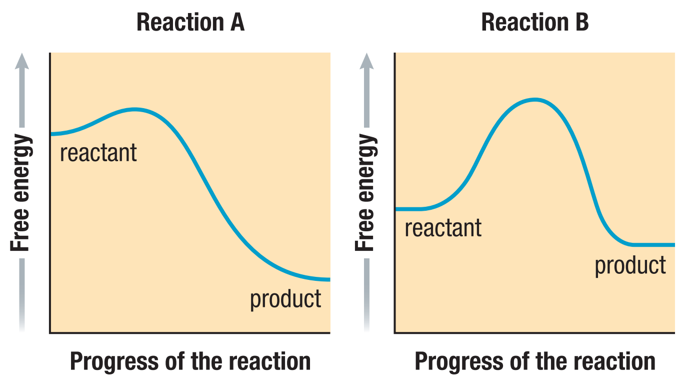


Figure 6

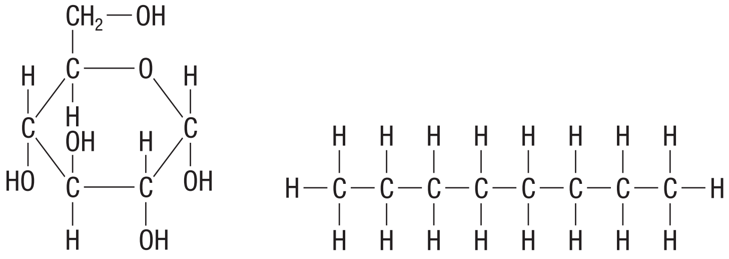
6. What are the three mechanisms by which an enzyme lowers the activation energy of a reaction? K/U
7. Draw and label a diagram to show how an enzyme can decrease the activation energy required for a reaction by bringing two reactants closer together. Share your diagram with your classmates. K/U C
8. Why is relying solely on increasing temperature not a good strategy to reach activation energy requirements in living organisms? What is the benefit of enzymes? K/U T/I
9. There is great interest in the use of enzymes in medical applications. Use the Internet and other sources to learn more about the potential uses of enzymes in the treatment of diseases. What are the benefits and drawbacks of using enzymes? Report your findings to the class. T/I C
10. Both mammals and birds are “warm-blooded” and maintain a body temperature that is usually significantly higher than the body temperatures of other animals. T/I
    (a) How would this influence the likelihood of chemical reactions taking place in their cells?
    (b) Why do mammals and birds still require enzymes?
11. Are you, or anyone you know, lactose intolerant? People with lactose intolerance sometimes make use of the enzyme lactase. Research the production of this important enzyme, and explain its value to people who are lactose intolerant. T/I

WEB LINK

Food as Fuel

3.4

What do gasoline and glucose have in common? What is it about the chemical makeup of gasoline and glucose that provides the energy needed to run a car or a cell? The one thing that glucose and gasoline have in common that makes them both good fuel molecules is an abundance of hydrogen in the form of carbon-hydrogen (C–H) bonds (**Figure 1**). As a result of their structure and bond type, there is a great deal of potential energy in both glucose and gasoline.



(a) glucose **(b)** octane

Figure 1 (a) Glucose and (b) octane (a component of gasoline) are valuable fuels due to the presence of easily accessible carbon-hydrogen (C–H) bonds.

Electrons in C–H bonds are a good source of energy because of their position and proximity to the relatively small atomic nuclei of carbon and hydrogen atoms. For any atom, an electron that is farther away from the nucleus contains more potential energy than an electron that is more closely held by the nucleus (**Figure 2**).

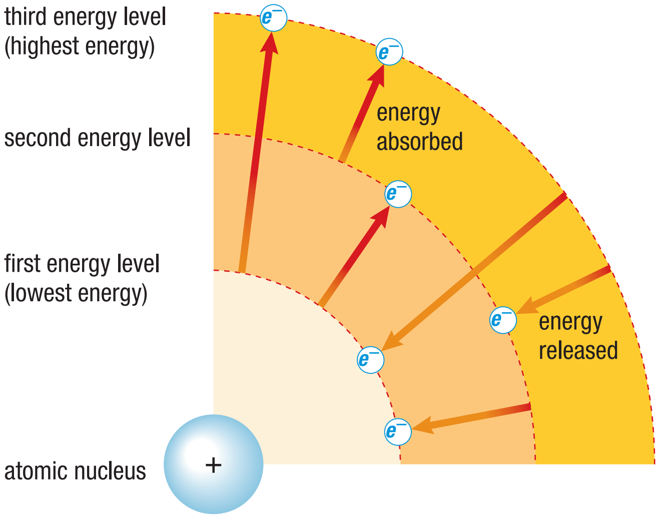


Figure 2 Electrons that absorb energy move to a higher energy level, which is farther away from the nucleus. Electrons that release energy move closer to the nucleus. Electrons can only exist in discrete energy states.

In addition to distance from the nucleus, the size of the nucleus influences the potential energy of an electron. An electron is more strongly attracted to a large nucleus than to a small nucleus. Therefore, at the same distance away, an electron has more potential energy relative to a large nucleus than relative to a smaller nucleus. As a result, an electron releases energy if it moves closer to a large nucleus and must gain energy to be pulled away.

The electrons associated with a C–H bond are approximately equidistant from two relatively small nuclei. As a result, the electrons in C–H bonds contain high energy. This is because they can be readily pulled closer to larger and more attractive nuclei—a process that releases energy. In contrast, molecules that already have an abundance of oxygen contain less potential energy because many of their bonding electrons are close to oxygen, which is strongly electronegative. The more electronegative an atom is, the greater the force of attraction it has to an additional electron (or electrons). In the case of an oxygen atom, two additional electrons from the atoms of other elements are able to get very close to the oxygen nucleus and are held very strongly. As the electrons in other atoms are attracted to the oxygen nucleus, they lose potential energy—releasing this energy during bond formation. After the additional electrons are in position close to the oxygen nucleus, the equivalent amount of energy would be required to remove them.

These fundamental principles of chemistry are relevant to everyday life. For example, they explain why fat contains more potential energy per unit of weight compared to proteins and carbohydrates. A fat molecule consists almost entirely of C–H bonds. Foods with a high fat content that are known to be high in energy include fatty fish (tuna or salmon), eggs, avocados, nuts, and meats. When cooking a high-energy food such as bacon, liquefied fat drains from the meat. This fat is highly flammable because of its high energy content, and it can cause a grease fire in your kitchen.

Energy Changes during Oxidation

Oxidation occurs when an atom or molecule loses electrons to another atom. The term "oxidation" comes from the fact that in many chemical reactions, the electrons within molecules, particularly those referred to as fuels, become bonded to an oxygen atom. Since O_2 has very high electronegativity, it is an ideal electron acceptor atom in the process of cellular respiration. The opposite of oxidation—known as reduction—occurs when an atom or molecule gains electrons. In a chemical reaction, the atom or molecule that gains electrons is called the oxidizing agent (that is, it oxidizes the other substance). The substance that loses electrons is known as the reducing agent (that is, it reduces the other substance).

As you learned in Chapter 1, in some redox reactions, electrons transfer completely from one molecule to another, while in other redox reactions, electrons remain shared between two atoms. The reaction between methane and oxygen illustrates a redox reaction in which the degree of electron sharing changes (**Figure 3**). Methane and oxygen are the reactants, and carbon dioxide and water are the products.

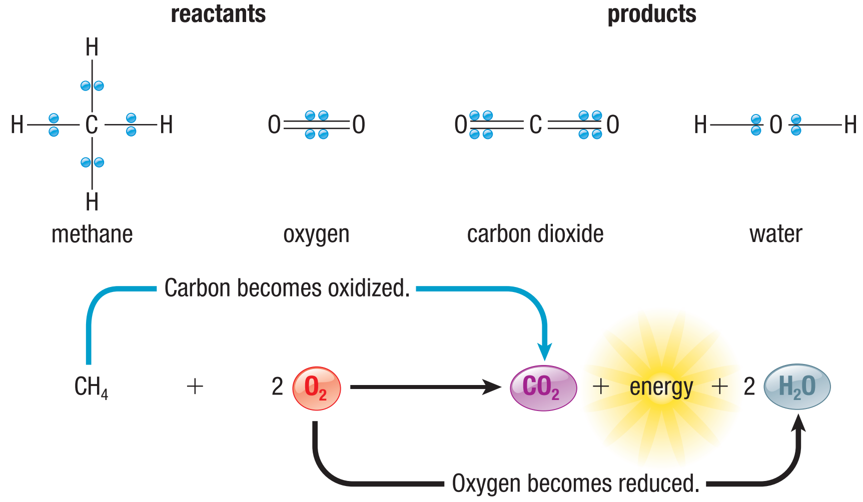


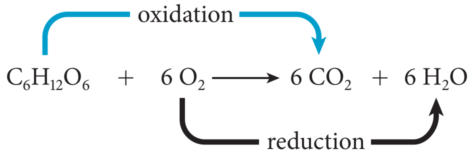
Figure 3 This diagram shows the relative loss and gain of electrons in a redox reaction in which methane reacts with oxygen. The carbon in the methane molecule is oxidized, and the oxygen is reduced. The dots indicate the positions of the electrons that are involved in the covalent bonds of the reactants and products.

In methane, the electrons are shared equally between bonded C–H atoms because C and H have almost the same electronegativity. Consider what happens to the electrons with respect to the carbon atoms. In the product CO_2, the electrons are drawn closer to the O atoms than to the C atoms because the O atoms are much more electronegative than the C atoms. Overall, this bond configuration means that C has partially lost its shared electrons in the reaction. The carbon atom within methane has been oxidized in this reaction.

Now look at the reactant oxygen and the product water. In the oxygen molecule, the two oxygen atoms share their electrons equally. The O_2 reacts with a hydrogen atom from methane. In the water molecule that is produced, the electrons are closer to the O atom than to the H atoms, due to the O atom's greater electronegativity. Therefore, the oxygen molecule has been reduced. The reaction releases a lot of energy because of the redox reaction that takes place between methane and oxygen. Energy is released when the electrons associated with the C–H bonds in methane move closer to the electronegative oxygen atoms that form CO_2 and H_2O.

The oxidation of fuel molecules, such as those in food, releases some of the potential energy stored within the molecule and allows it to be used for cellular processes. Redox reactions often involve the movement of electrons associated with hydrogen and oxygen atoms. Therefore, by convention, the removal of hydrogen atoms from, or the addition of oxygen atoms to, a molecule or atom is also called oxidation. Conversely, the addition of hydrogen or the removal of oxygen is called a reduction.

The following redox reaction describes the complete oxidation of glucose:



$$C_6H_{12}O_6 + 6\,O_2 \longrightarrow 6\,CO_2 + 6\,H_2O$$

Note that the carbons in the original glucose have lost their hydrogen atoms (along with the hydrogen atoms' electrons) and gained oxygen—they have been oxidized. In contrast, the oxygen atoms that were in the form of O_2 have now formed bonds with hydrogen and carbon—these oxygen atoms have been reduced. Energy is released from the glucose molecule as the high-energy carbon, and hydrogen electrons transfer to carbon dioxide and water, forming bonds with oxygen.

Rapid Combustion and Controlled Oxidation

Recall that during rapid oxidation, or the burning of fuels such as gasoline, it is oxygen gas itself that does the oxidizing. Glucose molecules can also undergo combustion and burn **(Figure 4(a)**, next page). Like all combustion reactions, the oxidation of glucose results in the transfer of electrons to O_2. The reaction produces CO_2 and H_2O and releases energy. CO_2 and H_2O are produced during the complete oxidation of all organic molecules. Since CO_2 and H_2O are both fully oxidized, they contain no more available chemical energy. When glucose burns, a large amount of waste thermal energy is released after an initial large energy of activation is overcome by a spark or flame.

An alternative to using rapid oxidation is to use the same overall reaction, resulting in similar end products, but with a series of steps. This is what happens inside cells, where the energy contained in food molecules is released through controlled oxidation. During controlled oxidation, cells are able to capture more free energy and produce less waste thermal energy. The energy contained in all the electrons in the C–H bonds is not liberated suddenly to produce a lot of thermal energy. In cells, the oxidation of glucose occurs through a series of enzyme-catalyzed reactions (**Figure 4(b)**, next page). Each step in these reactions releases a modest amount of energy following the absorption of a small amount of activation energy, which is provided by the thermal energy of the surroundings. The energy released transfers to energy-carrying molecules for the next step.

Thermodynamically, the net energy changes that occur in rapid combustion and controlled oxidation are identical. They are both exergonic reactions that have the same overall change in free energy. The difference is that, in the rapid combustion reaction, all of the energy is given off at once and cannot be as efficiently harnessed to drive metabolic reactions in the cell.

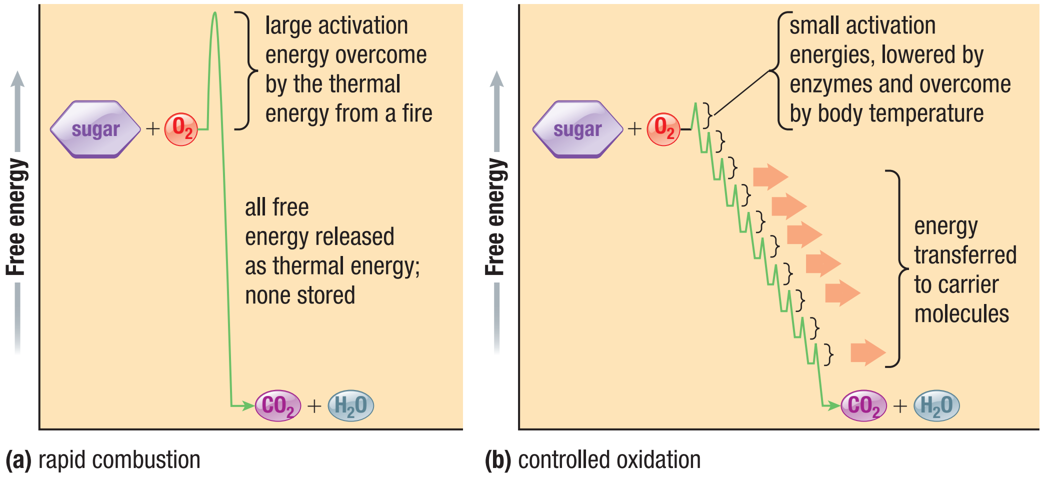

Free energy
sugar
O_2
large activation energy overcome by the thermal energy from a fire
all free energy released as thermal energy; none stored
CO_2
H_2O
(a) rapid combustion
Free energy
sugar
O_2
small activation energies, lowered by enzymes and overcome by body temperature
energy transferred to carrier molecules
CO_2
H_2O
(b) controlled oxidation

Figure 4 A comparison of the oxidation of glucose by (a) rapid combustion (burning) and (b) controlled oxidation

Energy Carriers

dehydrogenase an enzyme that oxidizes a substrate and transfers hydrogen ions to an acceptor

NADH the reduced form of the coenzyme nicotinamide adenine dinucleotide

The most important redox reactions in eukaryotic cells occur when glucose is oxidized by oxygen to form carbon dioxide and water. The oxidation of food molecules often uses enzymes called **dehydrogenases**, which facilitate the transfer of high-energy electrons from food to molecules that act as energy carriers or shuttles. The most common energy carrier molecule in cells is a positively charged coenzyme called nicotinamide adenine dinucleotide (NAD^+) (**Figure 5**). At various points during cellular respiration, dehydrogenases remove two hydrogen atoms from a substrate molecule, transferring the two high-energy electrons and only one of the protons (H^+) to NAD^+. The other H^+ is released into the cytosol. This process results in the full reduction to **NADH**. The efficiency of the transfer of energy between food molecules and NAD^+ is high, and very little energy is lost as waste thermal energy. As you will see later, the potential energy carried in NADH and other reduced molecules facilitates the synthesis of ATP. The next chapter examines these processes and related chemical pathways in more detail.

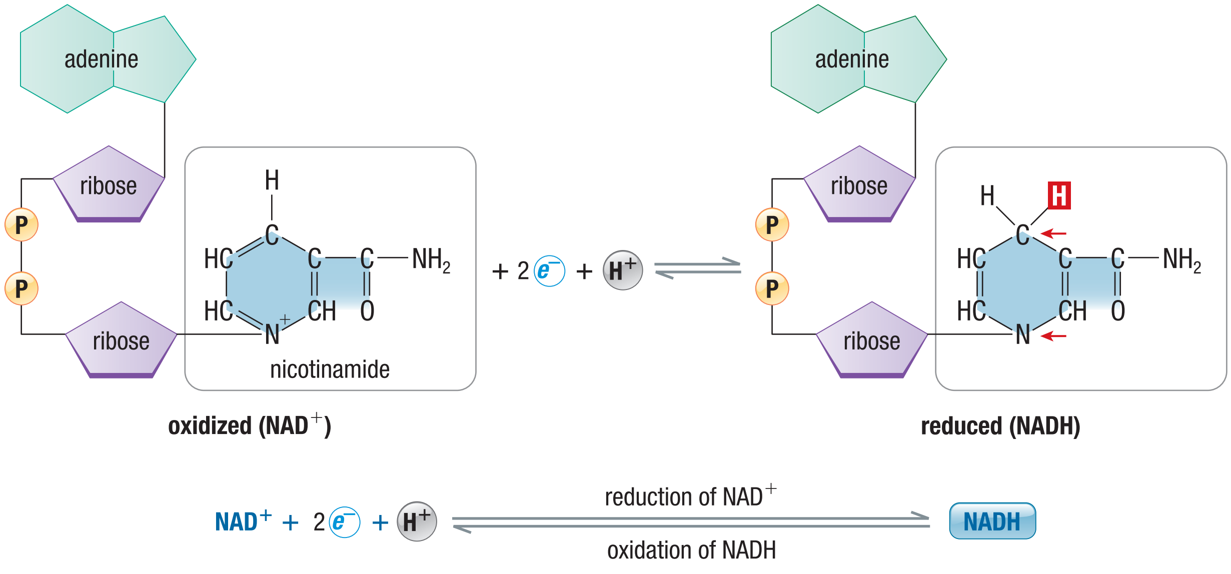


Figure 5 Structure of the electron carrier NAD^+ and its fully reduced form, NADH

3.4 Review

Summary

- Molecules with a large number of C–H bonds are high-energy molecules. Fat molecules have many C–H bonds and are a high-energy food source.
- Oxidation refers to the loss of electrons, and reduction refers to the gain of electrons.
- Potential energy that is stored in food molecules is released during oxidation reactions.
- Rapid oxidation reactions lead to a rapid loss of energy in the form of waste thermal energy. Controlled oxidation reactions involve many steps. There is less waste energy because more released energy can be captured effectively.
- During many cellular redox reactions, dehydrogenases facilitate the transfer of electrons from food to energy-carrier molecules.
- NAD^+ is a common high-energy electron carrier molecule in cellular processes, which is reduced to the form NADH. NADH provides a source of energy to drive ATP synthesis.

Questions

1. Explain, in your own words, why both gasoline and glucose make good fuels. K/U C
2. (a) Write the chemical equation for the complete combustion of glucose.
   (b) Which is the oxidizing agent?
   (c) Which is the reducing agent? K/U C
3. Use diagrams to explain how the relative positions of electrons change during a redox reaction, and how these positions are related to energy changes during the reaction. T/I C
4. Suggest a benefit provided by some of the waste energy that is released during cellular redox reactions. T/I A
5. Explain the gaining and releasing of energy by electrons, as related to changes in position relative to one or more atomic nuclei. T/I
6. In pairs, brainstorm examples of oxidation in everyday life that illustrate how reactive oxygen can be. A
7. List two examples of slow oxidation events and two examples of rapid oxidation events. T/I
8. Carefully examine Figure 5 on page 154. K/U T/I
   (a) What atom is reduced by gaining an electron during the reduction of NAD^+?
   (b) What atom is reduced by bonding to an added hydrogen atom?
   (c) Does this reaction influence any other atoms in the nicotinamide structure?
9. How is it beneficial for organisms to use controlled oxidation rather than rapid combustion to release energy from their food? Provide at least two benefits. K/U
10. You may have heard of antioxidants that aid in removing harmful oxidizing agents from the body. Many fresh fruits and vegetables are high in antioxidants (**Figure 6**). Conduct online research to find out how these antioxidizing agents do this. Why might this be important for proper cell functioning? K/U T/I

Figure 6 Antioxidant-containing foods

WEB LINK

Investigation 3.1.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

The Energy Content of Foods

Foods that we eat have different energy content and therefore release different amounts of energy when consumed. In this investigation, you will perform a quantitative analysis of the energy content of foods. For the purposes of this experiment, assume that the combustion of all foods produces only two products—carbon dioxide and water—and can be represented by the following equation:

food + oxygen → carbon dioxide + water

A calorimeter is a device that is used to measure the amount of thermal energy released during a reaction. By measuring the temperature difference before and after a reaction, the calorimeter indicates how much energy is released.

Testable Question

Which type of food releases the most energy per gram during complete combustion?

Prediction

Based on what you have learned about the energy content of reactions and the different types of biologically important molecules, write a prediction that addresses the testable question.

Variables

Read the Procedure. Identify all dependent (responding) variables and independent (manipulated) variables in this experiment.

Experimental Design

In this activity, you will construct a simple calorimeter and measure the temperature change of water as it is heated by the combustion of food items. Food items will be burned to heat the water in a can.

Equipment and Materials

SKILLS HANDBOOK A1.1, A1.2

- safety goggles
- protective gloves
- lab apron
- 10 cm by 10 cm piece of cardboard
- aluminum foil
- 2 large paper clips
- tape
- calorimeter (aluminum can, paper clip, string)
- ring stand
- thermometer
- electronic balance
- glass stirring rod
- room-temperature water (for calorimeter)
- food samples (dried fruit, popcorn, marshmallow, plain non-fat cracker, nut, sunflower seed)
- matches

Check for allergies before choosing foods. Be especially aware of allergies to nuts.

Use caution when lighting matches.

Procedure

SKILLS HANDBOOK A2.2

1. Put on your safety goggles, protective gloves, and lab apron.
2. Use a 10 cm by 10 cm piece of cardboard wrapped in aluminum foil, two large paper clips, and tape to build a food holder (**Figure 1**). Unfold a paper clip, straighten one end, and then bend over the curved end to about 90°. Push the straight end through the centre of the aluminum-foil square. Bend the straight end 90°, and tape it to the bottom of the foil to secure it. Repeat with the second paper clip, pushing it through the aluminum-foil square about 2 to 3 cm away from the first paper clip so that the ends of the paper clips, together, form a square. This will act as a platform for your food samples.

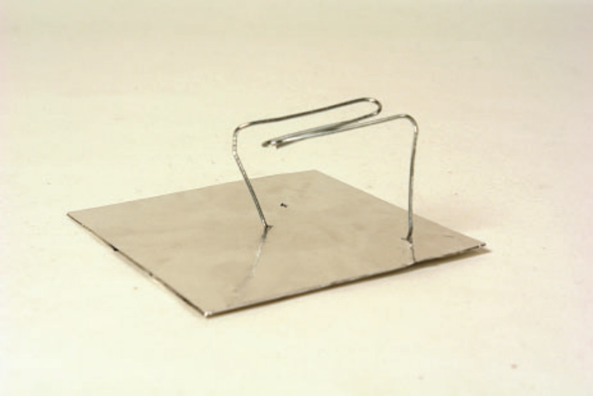


Figure 1 Food holder setup

3. Measure and record the mass of the empty aluminum can. Then add 100 mL of room-temperature water to the can and record the mass.
4. Use an unbent paper clip and string to hang the can from the ring stand.
5. Place the food sample on the paper clip food holder. Measure and record the mass of the food sample and the food holder.
6. Measure the temperature of the water in the can.
7. Place the food sample on its holder, under the aluminum can. Light a match and hold it to the food sample.

Keep hair and clothing away from flame.

8. Leave the sample under the can until it stops burning. Stir the water gently, and record the maximum temperature reached by the water.
9. Measure and record the mass of the burned food sample and the holder.
10. Repeat Steps 5 to 9 for all food samples. It is advisable to conduct two trials for each type of food. Be sure to add fresh room-temperature water to the can before each test. Be sure to measure the initial temperature during each trial.

Observations

Record all data and observations for each type of food tested. Include the mass of the food before and after burning, the temperature of the water before and after the food has been fully burned, and any additional physical observations of note.

Analyze and Evaluate

(a) (i) What were the independent, dependent, and controlled variables in this investigation?
  (ii) What type of relationship was being tested? T/I

(b) For each type of food, calculate the thermal energy absorbed by the water using the following equation:

$Q = mc\Delta T$, where

Q is the thermal energy absorbed in joules (J)

c is the specific heat of water, which is 4.186 J/g °C

m is the mass of the water in grams

ΔT is the change in temperature of the water in °C

Ignore the heating of the can because it has a low mass and low heat capacity, but note that this does introduce a small error in the calculations.

(c) Calculate the amount of energy released per gram from each type of food tested. T/I

(d) How did the different types of food compare? Was your prediction correct? Explain your answer. T/I

(e) Foods cannot be compared without determining the “per gram” values. Explain the reasoning behind this statement. T/I

(f) Explain your results in terms of the types of bonds and the relative bond energies found in carbohydrates, lipids, and proteins. T/I

(g) Describe what needed to be done to each food sample before it began to react on its own. Why is this not an option in living cells? T/I

(h) The match provided the initial activation energy to allow the food sample to combust. Where did the activation energy come from to keep the reaction going? T/I

(i) Do you think your results might have been different if there had been more or less water in the can? Explain your answer. T/I

Apply and Extend

(j) Were you surprised that the energy content of different types of food varied by such an amount? Why or why not? A

(k) (i) Conduct research online to determine the chemical composition of cellulose and a natural wax. Compare their energy content per gram. Consider their physical characteristics as well as their energy content.
  (ii) Why do you think these chemicals are not often used as a food source by humans?
  (iii) Conduct research to find out how bacteria and fungi are able to feed on cellulose. T/I

(l) Prepare and submit a complete writeup of your experiment, including the calculations of the thermal energy absorbed in each trial. C

WEB LINK

CHAPTER 3 SUMMARY

Summary Questions

1. Create a study guide based on the points listed in the margin on page 124. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 124. Answer these questions again, based on what you have learned in this chapter. Compare your answers to the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

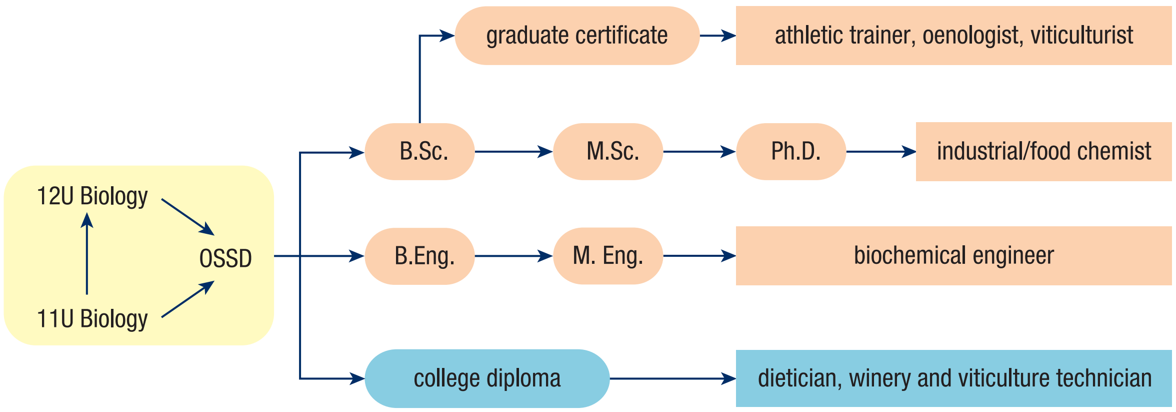
metabolism (p. 126)
kinetic energy (p. 126)
potential energy (p. 126)
first law of thermodynamics (p. 127)
bond energy (p. 128)
mole (p. 128)
activation energy (E_a) (p. 129)
transition state (p. 129)
exothermic reaction (p. 129)
endothermic reaction (p. 129)
second law of thermodynamics (p. 134)
entropy (p. 134)
spontaneous change (p. 135)
free energy (p. 136)
exergonic reaction (p. 137)
endergonic reaction (p. 138)
energy coupling (p. 138)
catabolic pathway (p. 139)
anabolic pathway (p. 139)
phosphorylation (p. 142)
ATP cycle (p. 144)
dehydrogenase (p. 154)
NADH (p. 154)

CAREER **PATHWAYS**

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to metabolism that you find interesting. Research the educational pathways you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, main duties and responsibilities, working conditions, and setting. Also outline how the career benefits society and the environment.



CAREER LINK

CHAPTER 3 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which of the following best describes metabolism? (3.1) K/U
   (a) the sum of the kinetic energy and potential energy in a cell
   (b) the sum of the chemical reactions in a cell
   (c) the sum of the exothermic reactions in a cell
   (d) the sum of the endergonic processes in a cell
2. Which of the following best describes energy? (3.1) K/U
   (a) the motion of objects
   (b) a force
   (c) the ability to do work
   (d) a type of electromagnetic radiation
3. If the value of ΔG is negative for an overall reaction, what does this indicate? (3.1) K/U
   (a) The reaction is non-spontaneous.
   (b) The reaction cannot occur.
   (c) The reaction requires additional energy.
   (d) The reaction is spontaneous.
4. Which type of bond is easiest to break, and is therefore found in molecules with a high energy content? (3.1) K/U
   (a) $O{-}H$
   (b) $C{=}O$
   (c) $O{=}O$
   (d) $C{-}H$
5. Which of the following best describes how ATP can be used to drive an endergonic reaction? (3.2) K/U
   (a) The endergonic reaction is coupled with the formation of ATP from ADP and P_i.
   (b) ATP is able to absorb free energy from the endergonic reaction.
   (c) The hydrolysis of ATP is coupled with the endergonic reaction.
   (d) ATP releases energy when it is phosphorylated by the endergonic reaction.
6. How do enzymes affect a reaction? (3.3) K/U
   (a) They increase the potential energy of reactants in a reaction.
   (b) They increase the activation energy of a reaction.
   (c) They lower the kinetic energy of reactants in a reaction.
   (d) They lower the activation energy of a reaction.
7. Which of the following best describes the relationship between an enzyme and a substrate? (3.3) K/U
   (a) stable
   (b) causes permanent alteration to the enzyme
   (c) results from non-complimentary bonding
   (d) temporary
8. Which process is used by cells to capture a greater percentage of the energy released from the oxidation of glucose? (3.4) K/U
   (a) spontaneous combustion
   (b) controlled oxidation
   (c) rapid oxidation
   (d) rapid reduction

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Gravitational potential energy may depend on the location or chemical composition of an object. (3.1) K/U
10. In an endothermic reaction, there is a net release of free energy. (3.1) K/U
11. The second law of thermodynamics states that every transfer or conversion of energy is 100 % efficient. (3.1) K/U
12. Endergonic reactions with a positive ΔG do not need to be coupled with an exergonic reaction to be spontaneous. (3.1) K/U
13. ATP is dehydrolyzed to release the energy in the food an organism ingests and then hydrolyzed to recover the ATP. (3.2) K/U
14. Phosphorylation of a molecule causes it to lose energy. (3.2) K/U
15. Thermal energy is the source of activation energy for most reactions. (3.3) K/U
16. Some enzymes change the shape of a substrate to weaken its chemical bonds and initiate a chemical reaction. (3.3) K/U
17. Carbohydrates are the food group with the highest energy content per gram. (3.4) K/U
18. Bonds with oxygen contain less potential energy than other bonds due to the high electronegativity of oxygen. (3.4) K/U
19. Fat contains more energy than carbohydrates and proteins because of the higher ratio of $C{-}C$ bonds. (3.4) K/U
20. In a redox reaction, the molecule that is oxidized gains electrons. (3.4) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 3 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which statement reflects the second law of thermodynamics? (3.1) K/U
   (a) The total amount of energy in the universe is always the same.
   (b) The total amount of entropy in the universe is always the same.
   (c) The entropy in the universe is always increasing.
   (d) The energy in the universe is always increasing.
2. Which of the following is the best definition of kinetic energy? (3.1) K/U
   (a) energy of motion
   (b) stored energy
   (c) chemical energy
   (d) vibrational energy
3. Which step is necessary for the initiation of a chemical reaction? (3.1) K/U
   (a) New bonds must form.
   (b) Bonds must be broken.
   (c) Water must be added.
   (d) Oxygen must be added.
4. Which of the following must you do when calculating the energy change during a reaction? (3.1) K/U
   (a) Write a balanced equation for the reaction.
   (b) Determine the number and type of bonds in the reactants.
   (c) Determine the number and type of bonds in the products.
   (d) all of the above
5. **Figure 1** shows a simplified depiction of the flow of energy in a chemical reaction. Which term best describes the reaction? (3.1) K/U
   (a) nonreversible
   (b) spontaneous
   (c) exothermic
   (d) endothermic

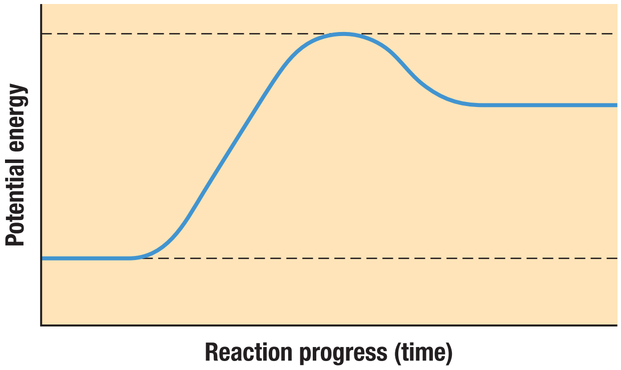


Figure 1

6. Which term best describes the overall change in free energy in an anabolic pathway? (3.1) K/U
   (a) constant
   (b) positive
   (c) negative
   (d) rapid
7. ATP synthesis is which of the following? (3.2) K/U
   (a) an endergonic process that phosphorylates ADP
   (b) an exergonic process that phosphorylates ADP
   (c) an endergonic process that dephosphorylates ATP
   (d) an exergonic process that dephosphorylates ATP
8. In which component of a coupled reaction is there a release of free energy? (3.2) K/U
   (a) hydrolysis of ATP
   (b) ADP phosphorylation
   (c) ATP synthesis
   (d) ADP synthesis
9. **Figure 2** depicts the same chemical reaction under different conditions. What is the difference between reaction 1 and reaction 2? (3.3) K/U
   (a) Reaction 1 is endothermic, and reaction 2 is exothermic.
   (b) A catalyst was added to reaction 1.
   (c) Reaction 1 is exothermic, and reaction 2 is endothermic.
   (d) A catalyst was added to reaction 2.

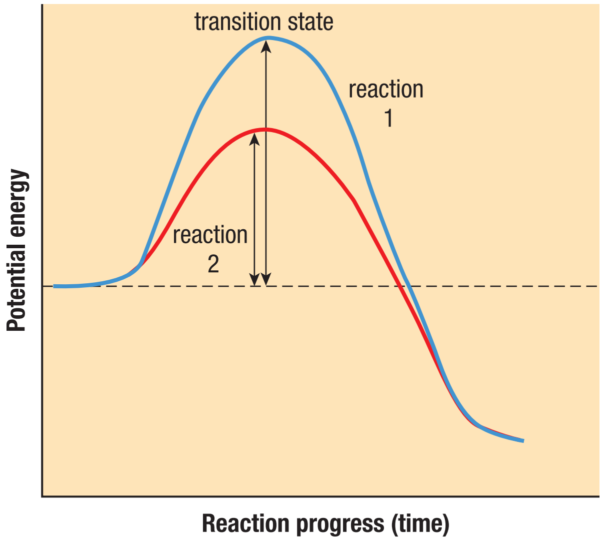


Figure 2

10. Which molecule facilitates the transfer of electrons during cellular respiration? (3.4) K/U
    (a) glucose
    (b) dehydrogenase
    (c) ATP
    (d) oxygen

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. In an endothermic reaction, the products contain less potential energy than the reactants. (3.1) K/U
12. The energy that is needed to break a bond is a reflection of the relative strength of the bond. (3.1) K/U
13. A spontaneous reaction results in an overall decrease in free energy. (3.1) K/U
14. A multi-step metabolic pathway generally consists of coupled biological reactions. (3.1) K/U
15. ATP hydrolysis is an example of an endergonic reaction. (3.2) K/U
16. Approximately 10 million ATP molecules are hydrolyzed and re-synthesized every day in a typical cell. (3.2) K/U
17. An ATP molecule contains free energy that can be used by a cell to do work. (3.2) K/U
18. The size of an enzyme is what mainly determines the function of the enzyme. (3.3) K/U
19. Glucose and gasoline are good fuel molecules because they have an abundance of easily broken C–H bonds. (3.4) K/U

Match each term on the left with the most appropriate description on the right.

20. (a) endergonic reaction
    (b) exergonic reaction
    (c) endothermic reaction
    (d) exothermic reaction

    (i) chemical reaction in which the thermal energy of the products is less than the thermal energy of the reactants
    (ii) chemical reaction in which the thermal energy of the products is greater than the thermal energy of the reactants
    (iii) chemical reaction that releases free energy
    (iv) chemical reaction that absorbs free energy (3.1) K/U

21. (a) energy coupling
    (b) phosphorylation
    (c) ATP cycle
    (d) free energy

    (i) addition of a phosphate group
    (ii) continuous breakdown and re-synthesis of ATP
    (iii) energy that can do useful work in a system
    (iv) transfer of free energy from one reaction to another (3.1, 3.2) K/U

22. (a) enzyme
    (b) oxidation
    (c) reduction
    (d) NADH

    (i) loss of electrons
    (ii) coenzyme that carries electrons from one reaction to another
    (iii) gain of electrons
    (iv) type of catalyst that speeds up biological reactions (3.3, 3.4) K/U

Write a short answer to each question.

23. (a) Which bond requires more energy to break: C–H or O–H? Explain your answer. (3.1) K/U
    (b) Which bond releases more energy when it forms: C–C or C–O? Explain your answer. (3.1) K/U
24. Is it possible for a catabolic pathway to have steps in which ΔG is positive? Explain your answer. (3.1) K/U
25. In your own words, explain the first and second laws of thermodynamics. (3.1) K/U
26. Describe the process of energy coupling, and explain why it is important. (3.2) K/U
27. Explain why the use of ATP as an energy source in cells is so widespread in the living world. (3.2) K/U
28. Explain how you can sometimes recognize an enzyme and its function by its name. Include one or two examples to support your explanation. (3.3) K/U
29. Summarize the three ways that an enzyme can help a reactant molecule reach the transition state. (3.3) K/U
30. Look at the graph of a chemical reaction in **Figure 3**. (3.3) K/U T/I
    (a) What part of the graph does each letter represent?
    (b) Is the reaction exothermic or endothermic? Explain.

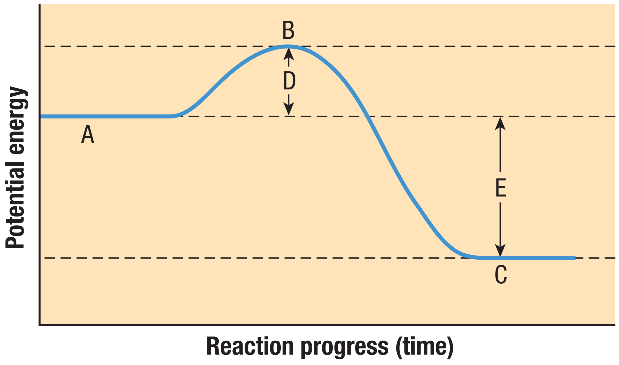


Figure 3

Understanding

31. Why is the process shown in **Figure 4** a good example of the first law of thermodynamics? (3.1) K/U

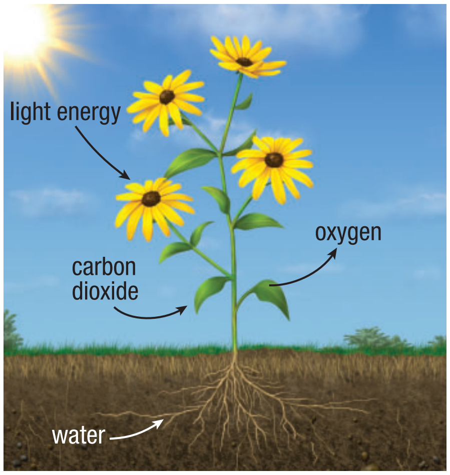


Figure 4

32. Explain why, even though energy is never created or destroyed, organisms must constantly consume energy-rich food molecules to survive. (3.1) K/U
33. (a) What is meant by the transition state of a reaction?
    (b) Explain what must be overcome for a reaction to achieve this state. (3.1) K/U
34. Suppose that you are asked to demonstrate a spontaneous endothermic process for a chemistry test. (3.1) K/U T/I A
    (a) Describe how you could do this.
    (b) How would your demonstration obey the second law of thermodynamics?
35. If entropy is always increasing, how can you explain the highly ordered structure of living organisms in an energy pyramid, such as the one shown in **Figure 5**? (3.1) K/U T/I

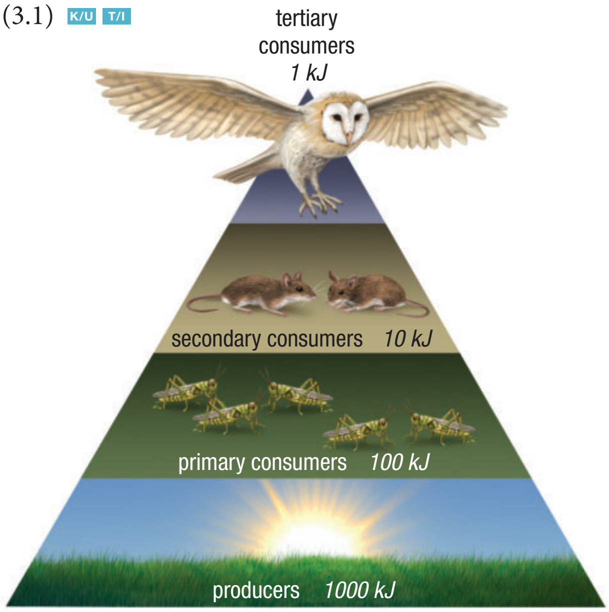


Figure 5

36. What does an exothermic reaction have in common with a reaction that increases entropy? (3.1) K/U
37. Copy and complete **Table 1** to compare free energy changes in anabolic and catabolic pathways. (3.1) K/U

Table 1

Type of pathway	Free energy (released or absorbed)	Relative size of product	Change in free energy (+ or –)
anabolic			
catabolic			

38. Discuss how changes in free energy are related to the capacity to do work. (3.1) K/U
39. Explain why photosynthesis is an example of an endergonic reaction. (3.1) K/U
40. Summarize the type of biological reactions that would depend on ATP for energy. (3.2) K/U
41. An endergonic reaction cannot occur spontaneously. Explain how ATP can help to drive an endergonic reaction. (3.2) K/U
42. Describe how ATP is used as the energy “currency” of all living cells. (3.2) K/U
43. In your own words, describe the ATP cycle. (3.2) K/U
44. Your teacher is performing an experiment in which the reaction is spontaneous. However, he still adds an enzyme to the substrate. Explain why he might do this. (3.3) K/U
45. What obstacle does the activation energy barrier present to a cell? (3.3) K/U
46. Explain the induced-fit model of enzyme activity. Include a sketch to illustrate your explanation. (3.3) K/U
47. Describe what can happen to a substrate once it is bound to an enzyme. (3.3) K/U
48. Based on what you have learned about enzyme activity, how do you think changes in substrate concentration, enzyme concentration, or environmental factors (such as temperature) might affect the rate of enzyme activity? Explain your answer. (3.3) K/U
49. Explain how an electron’s distance from the nucleus affects its potential energy. (3.4) K/U
50. Explain why fat molecules provide the highest source of energy of all types of food. (3.4) K/U A
51. Where would you find the chemical potential energy that is stored in food? (3.4) K/U
52. How is the potential energy that is stored within a molecule released? (3.4) K/U

53. Look at the process of glycolysis shown in **Figure 6**. (3.4) K/U T/I
    (a) Describe ΔG throughout the process.
    (b) Is this overall pathway catabolic or anabolic?

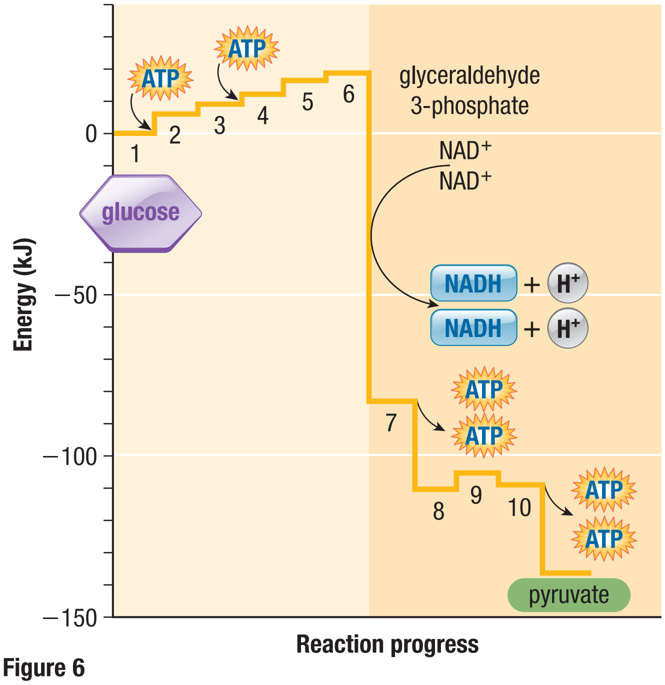


Figure 6

54. Explain the difference between combustion and controlled oxidation. (3.4) K/U

Analysis and Application

55. The first law of thermodynamics states that energy can be transformed from one form to another and transferred from one object to another. Explain the concepts of the first law of thermodynamics, using photosynthesis in plants as an example. (3.1) T/I

56. Calculate the net energy that is released by the complete combustion of the following compounds. Base your answer on the bond energy values in Table 1 on page 129. (3.1) T/I C
    (a) 1 mol of ethane gas
    (b) 1 g of fructose

57. Cells can use about 40 % of the energy that is released from the oxidation of glucose. (3.1) K/U T/I
    (a) Why do you think the oxidation of glucose is not more efficient?
    (b) How does your answer to part (a) relate to the second law of thermodynamics?

58. A student performs a reaction and finds that the free energy, G, of the reactants is 5672 kJ and the free energy of the products is 2347 kJ. Determine whether the reaction is spontaneous or non-spontaneous. (3.1) K/U

59. (a) Calculate the energy content, per gram, of the simple amino acid glycine, using the bond energies in Table 1 (page 129). The bond energy for a C—N bond is about 305 kJ/mol. The reaction for the oxidation of glycine is shown below (**Figure 7**).

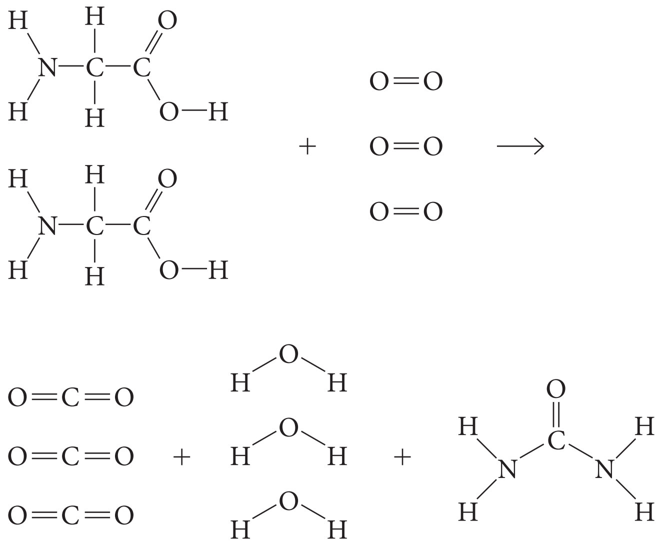


Figure 7

    (b) Calculate the energy content, per gram, of glucose. The reaction for the oxidation of glucose is shown below (**Figure 8**).

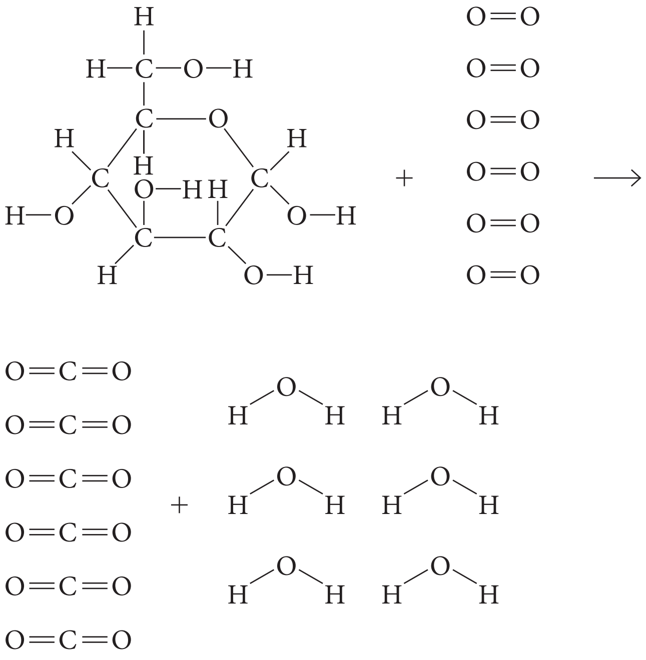


Figure 8

    (c) How does the energy content of glycine compare with the energy content of glucose?
    (d) What might this suggest about the energy content of carbohydrates and proteins? (3.1) K/U T/I

60. Cellular respiration converts glucose, which has a high level of free energy, to carbon dioxide and water, which have low levels of energy. (3.1) K/U
    (a) Is cellular respiration an exergonic reaction or an endergonic reaction?
    (b) Is it a spontaneous reaction?
    (c) What happens to all the energy from the glucose?
61. Suppose that your teacher asks you to find an object in nature with a highly ordered structure and to explain how the formation of this structure relates to the second law of thermodynamics. (3.1) T/I A
    (a) What is one object that you could find?
    (b) How does the structure of this object relate to the second law of thermodynamics?
62. What pattern can be used to describe the size of product molecules when comparing exergonic and endergonic products in a living thing? (3.2) K/U
63. Why might adding enzymes to laundry detergent help the environment (**Figure 9**)? (3.3) K/U T/I A

Figure 9

64. A scientist knows that a reaction occurs in living cells to break down hydrogen peroxide, which is a toxic chemical. She is attempting to duplicate the reaction in a lab. However, when she tries the reaction on its own, it is very slow. (3.3, 3.4) T/I A
    (a) Suggest one or two possible reasons to account for this.
    (b) What changes could she make to speed up the reaction?
65. (a) Based on what you have learned in Section 3.4, what type of bond do you think is abundant in olive oil?
    (b) What can this type of bond tell you about the energy content of olive oil? Explain your reasoning. (3.4) K/U T/I
66. Describe, in general terms, the changes that take place in the positions of electrons, relative to the nuclei, when the electrons go from being in a weak bond to being in a strong bond. (3.4) K/U T/I
67. In this chapter, you have learned about anabolic and catabolic pathways. Considering what you have learned, give possible reasons why some animals, such as some snakes, have to eat only once a month, whereas humans have to eat several times a day. Explain your thinking. (3.1, 3.4) T/I A
68. What are the advantages of consuming glucose rather than ATP as an energy-rich food source? In other words, why do organisms seek out and eat foods that are rich in sugars rather than eating foods that are rich in ATP? (3.2, 3.4) K/U T/I
69. Sometimes, a reaction requires the addition of a coenzyme, which is often a derivative of vitamins in the body. Suggest a role for coenzymes in a reaction. (3.3, 3.4) K/U A

Evaluation

70. You hear on the news that a person has claimed to have solved the world's energy problems by inventing a perpetual motion energy generator that will supply power to homes. Evaluate their claims using the laws of thermodynamics, and explain why it would be impossible to have a perpetual motion machine that is used to supply power to your home. (3.1) K/U T/I
71. Scientific studies of the digestive tract of the termite (**Figure 10**) have found bacterial enzymes that can break down complex carbohydrates, such as cellulose. Cellulose is the plant substance that is found in wood, and it is not digestible by most animals. Why might scientists be interested in these enzymes for the use of wood as an energy source? (3.3) T/I A

Figure 10 Termites feed on wood, causing significant damage.

72. Enzymes are commonly used in many aspects of agribusiness. In one application, fruits are picked unripe and treated with competitive inhibitors to prevent ripening. They are then later treated with a releasing agent when it is desirable to have the fruit ripened. (3.4) K/U T/I A
    (a) Who benefits from this practice? Explain your answer.
    (b) Evaluate the environmental implications of this practice.
    (c) Fruits and other foods treated with enzymes currently do not require labelling. Do you think they should be? Explain your position.
73. A chemical engineer has to choose a crop that can be developed as a biofuel. Crop X produces a large quantity of a compound that contains many C–C and C–H bonds but very few C=O bonds. Crop Y produces a similar compound, but this compound contains a significantly higher number of C=O bonds. Which crop should the engineer choose? Explain your reasoning. (3.1, 3.3) T/I A

Reflect on Your Learning

74. After learning about how enzymes function, are you more likely to purchase detergents that contain enzymes? Explain why or why not. K/U T/I
75. How do you see our reliance on enzymes changing as the global population increases? Do you think this will be an advantage or a disadvantage to society? K/U T/I
76. (a) What one topic covered in this chapter would you like to explore in more depth? What interests you about this area?
    (b) Research possible job opportunities related to this topic. K/U T/I

Research

WEB LINK

77. One technique that doctors can use to care for wounds is known as enzymatic debridement. Conduct research to find out more about this technique. What are the advantages and disadvantages of enzymatic debridement, compared with other types of debridement? T/I A
78. Research teeth whiteners and pre-digested baby food. These products are dependent on enzymes for either their production or their function. Explain the role of the enzymes in each product. T/I
79. Research the energy demands of muscle cells, brain cells, and fat cells. K/U T/I A
    (a) Compare the energy demands of these three types of cells.
    (b) Describe what the energy demand tells you about the rate of ATP consumption in each type of cell.
80. Enzymes are used extensively in industry to help prepare food for market. In the commercial preparation of meat, for example, two commonly-used enzymes are papain (from papaya) and bromelain (from pineapples). Conduct online research to find out more about how enzymes are used in food processing. While you conduct your research, play the role of a Health Canada researcher who has been asked to prepare a press release on the use of these enzymes in Canada. Your press release should include the following:
    - an explanation of how the enzymes work
    - a list of what foods commonly found in grocery stores contain the enzymes
    - the labelling requirements for food containing these enzymes
    - your position on the use of these enzymes in food production in Canada K/U T/I C A
81. Many enzymes in our body require the addition of a cofactor to function, or to function at peak efficiency. Use the Internet and other sources to research one of these cofactors and how it helps enzyme function. Use your research to develop a marketing campaign to promote the cofactor you have chosen to research. Present your campaign in the form of a short multimedia presentation. As you conduct your research, consider the following questions:
    - How does the cofactor work?
    - What is competitive inhibition?
    - What is the target market for the cofactor you have chosen to research?
    - Is the cofactor you have chosen to research beneficial to society? K/U T/I C A

CHAPTER

4 Cellular Respiration

KEY CONCEPTS

After completing this chapter you will be able to

- describe how cellular respiration is a process comprising pathways that allow cells to convert energy stored in food molecules into energy stored in ATP
- explain the four stages of aerobic cellular respiration: glycolysis, pyruvate oxidation, the citric acid cycle, and the electron transport chain coupled with chemiosmosis
- understand why anaerobic respiration and fermentation facilitate energy transfer in the absence of oxygen
- list the main reactants and products in the reactions that make up cellular respiration and fermentation, and explain how much energy is ultimately retrieved from simple sugars
- understand how the cells in your body adjust their energy transfer depending on your activity level and diet, and how they synthesize important molecules that are not obtained from food

How Do Cells Extract Energy from Their Food?

In the early 1960s, Swedish physician Rolf Luft was consulted by a patient with some odd symptoms. The young woman was hot all the time, even on the coldest winter days. She never stopped perspiring, and her skin was always flushed. As well, she felt weak and was thin, despite a huge appetite.

Luft inferred that the patient's symptoms pointed to a metabolic disorder. Her cells were clearly metabolizing food, but much of their activity was being dissipated as metabolic thermal energy. He ordered tests to measure her metabolic rates. The patient's oxygen consumption was the highest ever recorded! Luft also examined a tissue sample from the patient's muscles. Using a microscope, he found that her muscle cells contained many more mitochondria—the ATP-producing organelles of the cell—than normal. In addition, her mitochondria were abnormally shaped. Other tests showed that the mitochondria were engaged in cellular respiration—their prime function—but little ATP was being generated.

The disorder, now called Luft syndrome, was the first disorder to be linked directly to a defective cellular organelle. Luft syndrome is extremely rare. It is caused by a defect in the protein machinery that is involved in cellular respiration. This protein machinery is part of a chain of steps that take place along and across the inner mitochondrial membrane, resulting in ATP production. In patients with Luft syndrome, tissues with the highest energy demands, including heart and skeletal muscle and brain tissue, are affected the most.

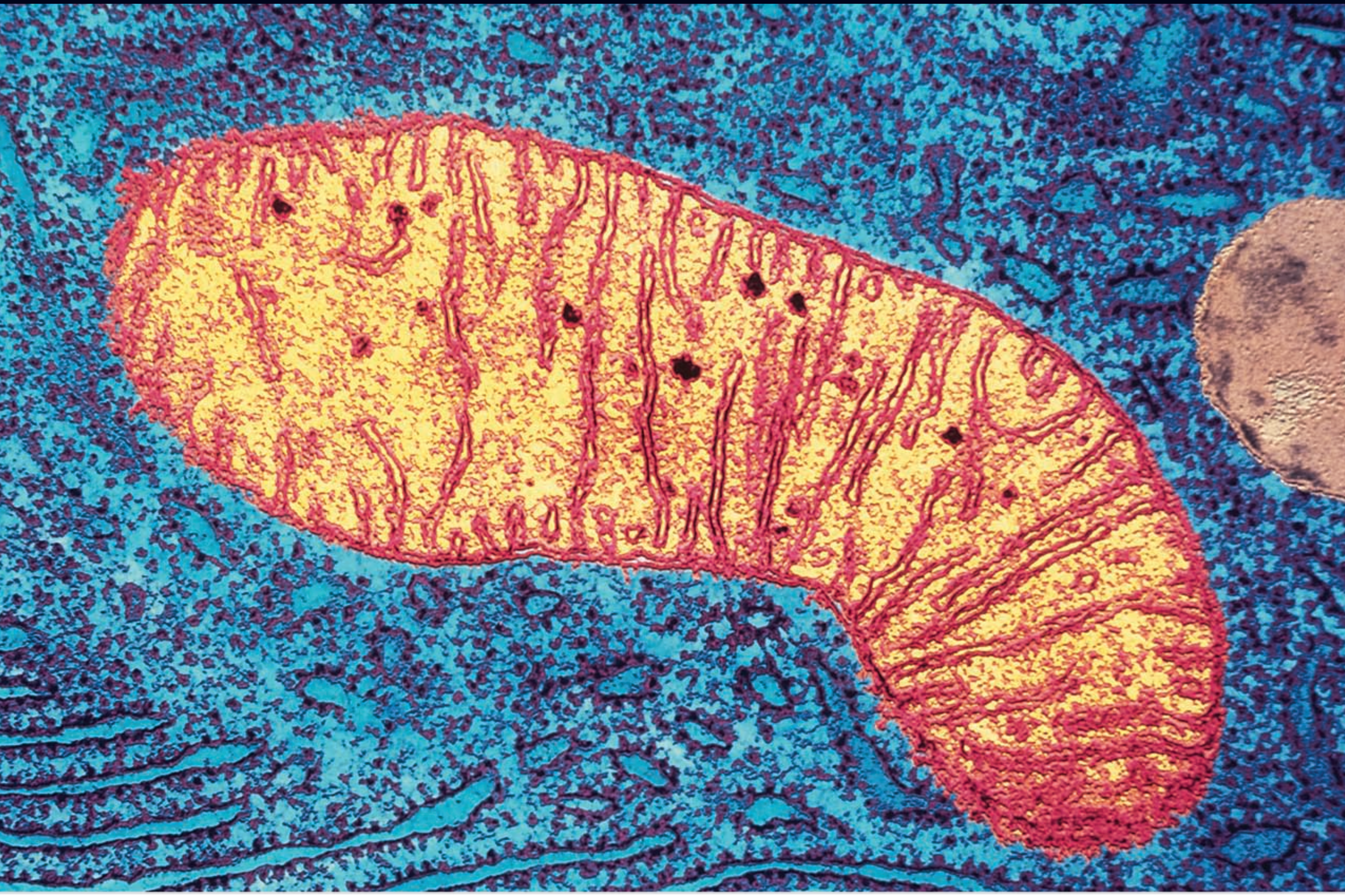
Remember that mitochondria (singular: mitochondrion) contain their own DNA, which can be affected by mutations that lead to mitochondrial-specific disorders. More than 100 mitochondrial disorders are now known. Defective mitochondria also contribute to many age-related problems, including Parkinson's, Alzheimer's, and Huntington's diseases; type 1 diabetes; atherosclerosis; and amyotrophic lateral sclerosis (ALS, also called Lou Gehrig's disease).

Clearly, human health depends on the mitochondria being structurally sound and functioning properly. In fact, every animal, plant, and fungus, and most protists, depend on their mitochondria properly producing ATP to survive. In this chapter, you will learn about cellular respiration and ATP production in living organisms. You will examine the various pathways by which energy in food is harnessed to make ATP, including aerobic respiration, anaerobic respiration, and fermentation.

STARTING **POINTS**

Answer the following questions based on your current knowledge. You will have a chance to revisit these questions later, applying the concepts and skills you have learned in the chapter.

1. Consider the amount of food you consume each and every day. Do you notice a corresponding weight gain each day? What does this suggest about the main role of food consumption? Is it to provide energy? Is it to grow?
2. Why is oxygen necessary for our lives? What are some of the ways that oxygen is used in the cells of the human body and other living organisms?
3. We need oxygen, water, and food from our environment, but only oxygen must be taken in continuously because it cannot be readily stored in the body.
   (a) If we stop breathing, how long can we live? What does this suggest about the consumption rate of oxygen gas within the body?
   (b) Where is oxygen transported in the body? Why can it not be stored?



Mini Investigation

Exploring Energy Demands

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK **A2.1, A5.4**

In this investigation, you will work with a partner to perform an experiment and answer questions that will help you understand the importance of oxygen for physical activity. You will experience what happens to muscles as the oxygen that is available to mitochondria is reduced over time.

Equipment and Materials: stress ball; stopwatch

1. Place the stress ball in the palm of your dominant hand.
2. Count the number of times that you can squeeze the stress ball in 20 s.
3. Without resting, repeat Step 2 nine more times. Have your partner record the number of times that you can squeeze the ball in each trial. Also have your partner record how your hand feels at the end of each trial.
4. Repeat Steps 1 to 3 using your non-dominant hand.

A. Graph the number of squeezes (along the *y*-axis) in each trial (along the *x*-axis). T/I C

B. Did your results change over time? Why? T/I

C. Did your results differ between your dominant hand and non-dominant hand? Explain why they did or did not. T/I

D. Suggest a reason why your hand muscles may have begun to run low on oxygen even though you continued to breathe. T/I

E. What could you change to help maintain a consistent pace of squeezes? T/I

4.1

Introduction to Cellular Respiration and Fermentation

Forest fires release an enormous amount of energy. The major component of the wood that burns is cellulose. Cellulose molecules, the main component of plant cell walls, are complex carbohydrates made of glucose. When cellulose burns, it combines with oxygen gas in the atmosphere and releases a tremendous amount of potentially life-threatening energy. When animals eat plants, what happens to all of this stored energy? What pathways allow them to extract energy from their food without literally burning up? In this chapter, you will examine the fundamental biological processes that enable organisms to extract energy from molecules such as glucose.

Most of the energy that enters the biosphere is solar radiation. The process of photosynthesis (which you will study in Chapter 5) transforms this light energy into chemical potential energy, which is then available to plants and other organisms in food webs. Photosynthesis captures light energy and uses it to convert carbon dioxide and water into organic molecules, such as sugars, that contain an abundance of free energy (**Figure 1**).

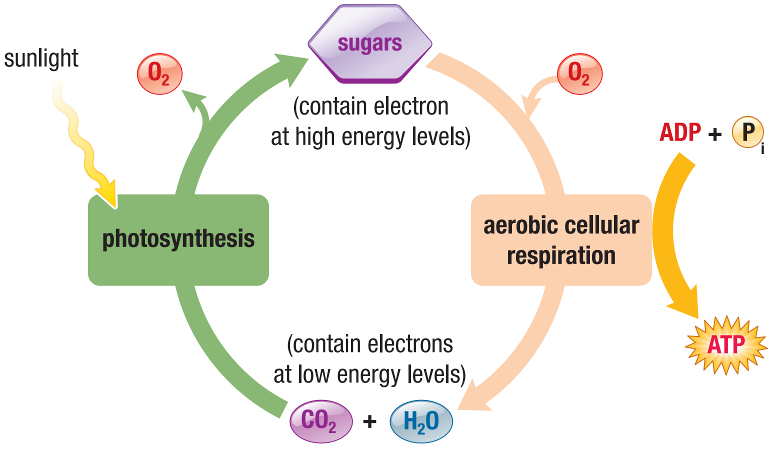

sunlight
O_2
sugars
(contain electron at high energy levels)
O_2
ADP + P i
photosynthesis
aerobic cellular respiration
ATP
(contain electrons at low energy levels)
CO_2 + H_2O

Figure 1 The flow of energy from sunlight to ATP

The immediate products of photosynthesis, sugars and O_2, are used in energy-releasing reactions in aerobic cells. Potential energy is extracted from these food molecules through oxidation and is used to synthesize adenosine triphosphate (ATP). The chemical energy, which is now stored in ATP, can readily be released and used by the cell for most of the activities that require energy. When O_2 is unavailable, anaerobic cells have alternative ways to release energy from food molecules.

Aerobic Cellular Respiration

aerobic cellular respiration a process that uses oxygen to harvest energy from organic compounds

Aerobic cellular respiration (or, simply, aerobic respiration) is the process that extracts energy from food in the presence of oxygen (Figure 1). The energy is used to synthesize ATP from ADP and P_i. The ATP molecules are then used to supply energy directly to the cells for their energy-demanding activities. As shown in the following equation, carbon dioxide and water are released as waste products in the reaction. Gibbs free energy is also released and is used to make ATP.

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O \qquad \Delta G = -2870\ \text{kJ/mol}$$

obligate aerobe an organism that cannot live without oxygen

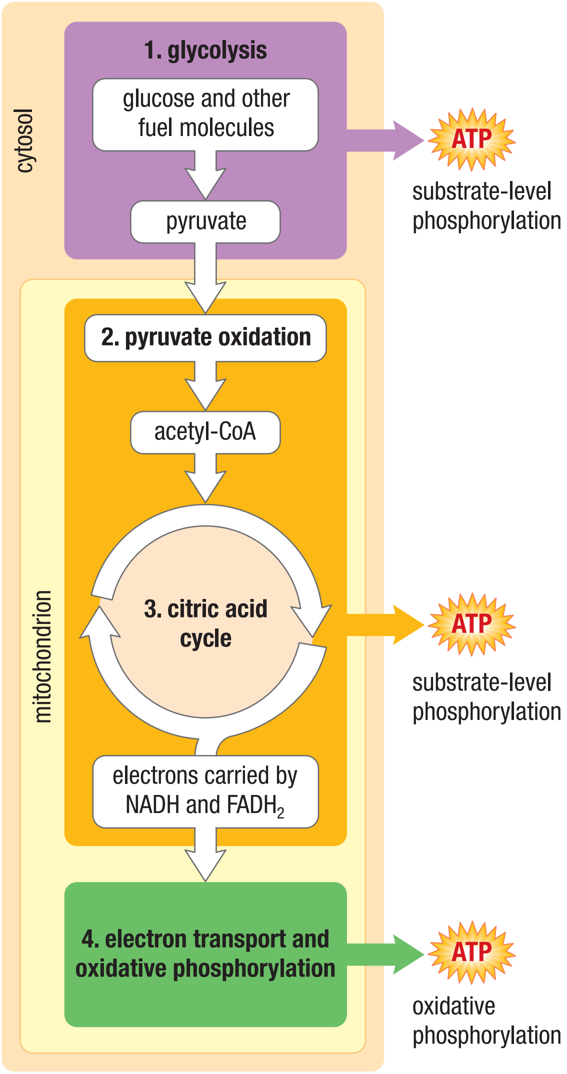
Aerobic cellular respiration takes place in most eukaryotes and some prokaryotes. Most eukaryotes, including all plants and animals, are **obligate aerobes**: they cannot live without oxygen, and they use aerobic cellular respiration exclusively or most of the time.

Later in the chapter, you will learn that proteins and lipids can also be oxidized by cells as a source of potential energy. However, because the oxidation of glucose is the most widely used pathway, it is the focus of our discussion.

Aerobic cellular respiration can be divided into four stages (**Figure 2**). Each stage involves the transfer of free energy, producing ATP in one of two ways: substrate-level phosphorylation and oxidative phosphorylation. **Substrate-level phosphorylation** forms ATP directly in an enzyme-catalyzed reaction through the transfer of a phosphate group from one molecule to an adenosine diphosphate (ADP) molecule. **Oxidative phosphorylation** forms ATP indirectly through a series of redox reactions involving a final electron acceptor. In aerobic respiration, oxygen is the final electron acceptor. You will learn about aerobic cellular respiration in Sections 4.2 and 4.3.

substrate-level phosphorylation the formation of ATP by the direct transfer of a phosphate group from a substrate to ADP

oxidative phosphorylation a process that forms ATP using energy transferred indirectly from a series of redox reactions


cytosol
1. glycolysis
glucose and other fuel molecules
pyruvate
ATP
substrate-level phosphorylation
mitochondrion
2. pyruvate oxidation
acetyl-CoA
3. citric acid cycle
ATP
substrate-level phosphorylation
electrons carried by NADH and FADH$_2$
4. electron transport and oxidative phosphorylation
ATP
oxidative phosphorylation

1. Glycolysis (in cytosol). Enzymes break down one molecule of glucose into two molecules of pyruvate. Some high-energy ATP (via substrate-level phosphorylation) and NADH is synthesized.

2. Pyruvate oxidation (in mitochondria). Each of the two molecules of pyruvate produced in glycolysis is transported to mitochondria and is oxidized, resulting in the production of CO_2 (a waste molecule), NADH, and an acetyl group that is initially attached to coenzyme A (acetyl-CoA).

3. Citric acid cycle (in mitochondria). Acetyl-CoA molecules from pyruvate oxidation enter a metabolic cycle, where the acetyl group is completely oxidized to CO_2. In the process, ATP (via substrate-level phosphorylation) and the electron carriers NADH and $FADH_2$ are synthesized.

4. Electron transport and oxidative phosphorylation (in mitochondria). The NADH and $FADH_2$ (synthesized during glycolysis, pyruvate oxidation, and the citric acid cycle) are oxidized. Their high-energy electrons and hydrogens are passed from one oxidizing agent to the next until they are transferred to O_2, producing water. The free energy released during electron transport is indirectly used to synthesize a large amount of ATP by oxidative phosphorylation.

Figure 2 This greatly simplified flow diagram shows the four stages of cellular respiration.

glycolysis a series of reactions in which a glucose molecule is broken into two pyruvate molecules and energy is released

pyruvate oxidation a reaction in which pyruvate is oxidized by NAD^+, and CO_2 is removed, forming an acetyl group and releasing NADH

citric acid cycle a cyclic series of reactions that transfers energy from organic molecules to ATP, NADH, and $FADH_2$ and releases carbon atoms as CO_2

The Mitochondrion

In eukaryotic cells, glycolysis occurs in the cytosol, whereas pyruvate oxidation, the citric acid cycle, and electron transport occur in the mitochondrion. This membrane-bound organelle is often referred to as the powerhouse of the cell because, as the location of the citric acid cycle and electron transport, it generates most of the ATP that is used by the cell. The mitochondrion is composed of two membranes, the outer membrane and the inner membrane, which together define two compartments (**Figure 3**). The intermembrane space is between the outer and inner membranes, and the matrix is the interior aqueous environment of the organelle.

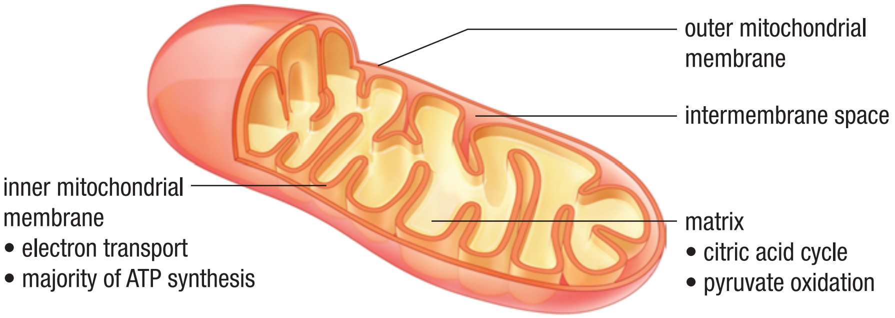


Figure 3 The membranes and compartments of the mitochondrion

Some prokaryotes undergo aerobic cellular respiration without mitochondria. In prokaryotes, the process of glycolysis, pyruvate oxidation, and the citric acid cycle occur in the cytosol of the cell, whereas electron transport occurs on internal membranes that are derived from the plasma membrane. These prokaryotes possess the full complement of reactions that make up aerobic cellular respiration—from glycolysis through electron transport and oxidative phosphorylation.

Anaerobic Pathways

anaerobic respiration a process that uses a final inorganic oxidizing agent other than oxygen to produce energy

fermentation a process that uses an organic compound as the final oxidizing agent to produce energy

Energy can be extracted from food molecules through a number of biochemical pathways. As well as using aerobic cellular respiration, which requires the presence of oxygen, many organisms can extract energy from food without using oxygen. There are two general processes by which certain cells can oxidize fuel molecules and generate ATP in the absence of oxygen: anaerobic respiration and fermentation. **Anaerobic respiration** is similar to aerobic cellular respiration in using a series of electron-transferring steps, but it uses an inorganic molecule other than oxygen as the final oxidizing agent. **Fermentation** does not use an electron transport system. It relies on an organic compound to act as the final oxidizing agent. Both anaerobic respiration and fermentation are catabolic (energy-yielding) processes. The following equation shows the overall reaction for one common fermentation pathway. The released free energy is used to make ATP. Notice that the products of this fermentation pathway are ethanol, CH_3CH_2OH, and CO_2:

$$C_6H_{12}O_6 \rightarrow 2\ CH_3CH_2OH + 2\ CO_2 \qquad \Delta G = -218\ \text{kJ/mol}$$

There is a striking difference between the small amount of free energy that is released by this fermentation pathway and the amount released during aerobic cellular respiration.

obligate anaerobe an organism that cannot survive in the presence of oxygen

facultative anaerobe an organism that can live with or without oxygen

Many prokaryotes and some protists live in environments with little or no oxygen. They use anaerobic respiration or fermentation to obtain energy from their food. Examples of these organisms are the bacteria that are responsible for tetanus and botulism poisoning, and the protist *Trichonympha*, which lives within the guts of termites and feeds on ingested cellulose. *Trichonympha* lacks mitochondria and relies on an unusual fermentation pathway to generate ATP. All of these organisms are **obligate anaerobes** and cannot survive in the presence of oxygen. They use inorganic substances such as NO_2, S, and Fe^{3+} as final electron acceptors to obtain energy. Other organisms, such as yeast and the *E. coli* bacteria that live in our gut, survive with or without oxygen. These organisms are called **facultative anaerobes**. You will learn more about the anaerobic respiration and fermentation processes in Section 4.4.

4.1 Review

Summary

- There are three main types of energy pathways: aerobic respiration, anaerobic respiration, and fermentation. They all produce ATP.
- The four stages of aerobic cellular respiration are glycolysis, pyruvate oxidation, the citric acid cycle, and the electron transport chain.
- Mitochondria generate most of the ATP that is used in eukaryotic cells.
- Respiration pathways use electron transport systems to generate ATP by oxidative phosphorylation. Fermentation pathways lack such transport systems.
- Anaerobic respiration uses an inorganic substance other than oxygen as the final oxidizing agent. Fermentation relies on an organic compound.

Questions

1. (a) What is the final energy-rich product of the pathways that extracts energy from food?
   (b) What is this product responsible for in the cell? K/U
2. Explain the main difference between aerobic respiration and anaerobic respiration. K/U
3. Use a Venn diagram to compare and contrast anaerobic respiration with fermentation. K/U
4. Describe the differences between the following:
   - obligate aerobes
   - obligate anaerobes
   - facultative anaerobes K/U
5. (a) What is the overall equation that represents aerobic cellular respiration?
   (b) Describe this equation using simple words that a non-scientist could understand. K/U C
6. How many stages are involved in aerobic cellular respiration? Briefly describe each stage. K/U
7. Some bacteria cells are quite similar in structure to mitochondria. Both contain their own DNA, and both are able to divide on their own (mitochondria divide within eukaryotic cells). However, bacteria cells are able to survive independently, while mitochondria are not. K/U T/I
   (a) What part of the aerobic respiration pathway cannot be performed by mitochondria?
   (b) In terms of energy pathways only, what two chemicals (in addition to ADP and P_i) do mitochondria need to take in to generate ATP?
8. Suggest a commercial application of a fermentation pathway. A
9. Using the Internet and other sources, research commercial ethanol production. How could using bacteria to generate ethanol through cellulosic fermentation lead to a more efficient method of producing ethanol as a biofuel? T/I A
10. What would be the net effect for life on Earth if the aerobic pathway had not developed? T/I A

WEB LINK

4.2 Aerobic Respiration: The Details

The process of aerobic respiration extracts the energy that your body needs from simple food molecules. Of the many thousands of chemical reactions that take place in living cells, the reactions that make up aerobic respiration are among the most essential. They take place in every oxygen-breathing organism on Earth. In fact, aerobic respiration made the evolution of large animals possible because it allowed them to meet their very high energy demands.

As you read this section, remember that every one of your billions of active cells requires access to more than one million ATPs per second! Those ATPs are generated within each cell by aerobic cellular respiration. In this section, you will learn about the four stages of aerobic cellular respiration: glycolysis, pyruvate oxidation, the citric acid cycle, and the electron transport chain. You will learn how the energy that is released during the final stage drives most ATP synthesis.

Glycolysis

Glycolysis is the first set of reactions for extracting energy from sugar molecules. It is considered to be the most fundamental and probably most ancient of all metabolic pathways. This is supported by the following facts. First, glycolysis is nearly universal, being found in almost all organisms, both prokaryotes and eukaryotes, from all branches of the tree of life. Second, it does not require O_2. Oxygen became abundant in Earth's atmosphere only about 2.5 billion years ago—about 1.5 billion years after scientists think that life began. Third, glycolysis occurs in the cytosol of all cells and involves soluble enzymes. Therefore, it does not require more sophisticated cellular organelles in order to operate.

Glycolysis is one of the first metabolic pathways that was studied and is one of the best understood, in terms of the enzymes involved, their mechanisms of action, and the regulation of the pathway to meet the energy needs of the organism. The first experiments investigating glycolysis took place over 100 years ago. Using extracts from yeast cells, researchers showed that they could study biological reactions in an isolated system. These experiments became the foundation of modern biochemistry.

The Reactions of Glycolysis

Glycolysis consists of 10 sequential enzyme-catalyzed reactions that lead to the oxidation of the 6-carbon sugar glucose, producing two molecules of the 3-carbon compound pyruvate. The potential energy and electrons released in the oxidation leads to the overall synthesis of both ATP and NADH. Glycolysis has two phases: an initial energy investment phase followed by an energy payoff phase (**Figure 1**). Both the initial energy investment phase and the energy payoff phase have five steps (**Figure 2**, next page).

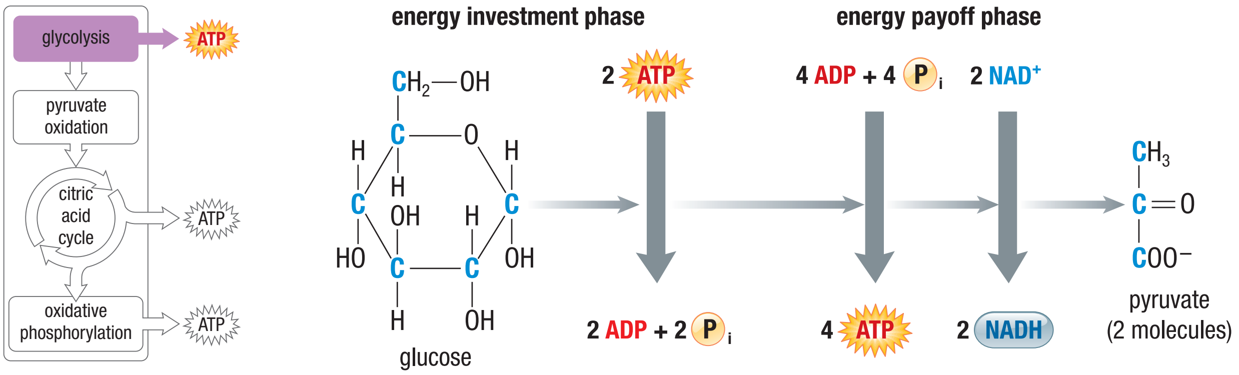
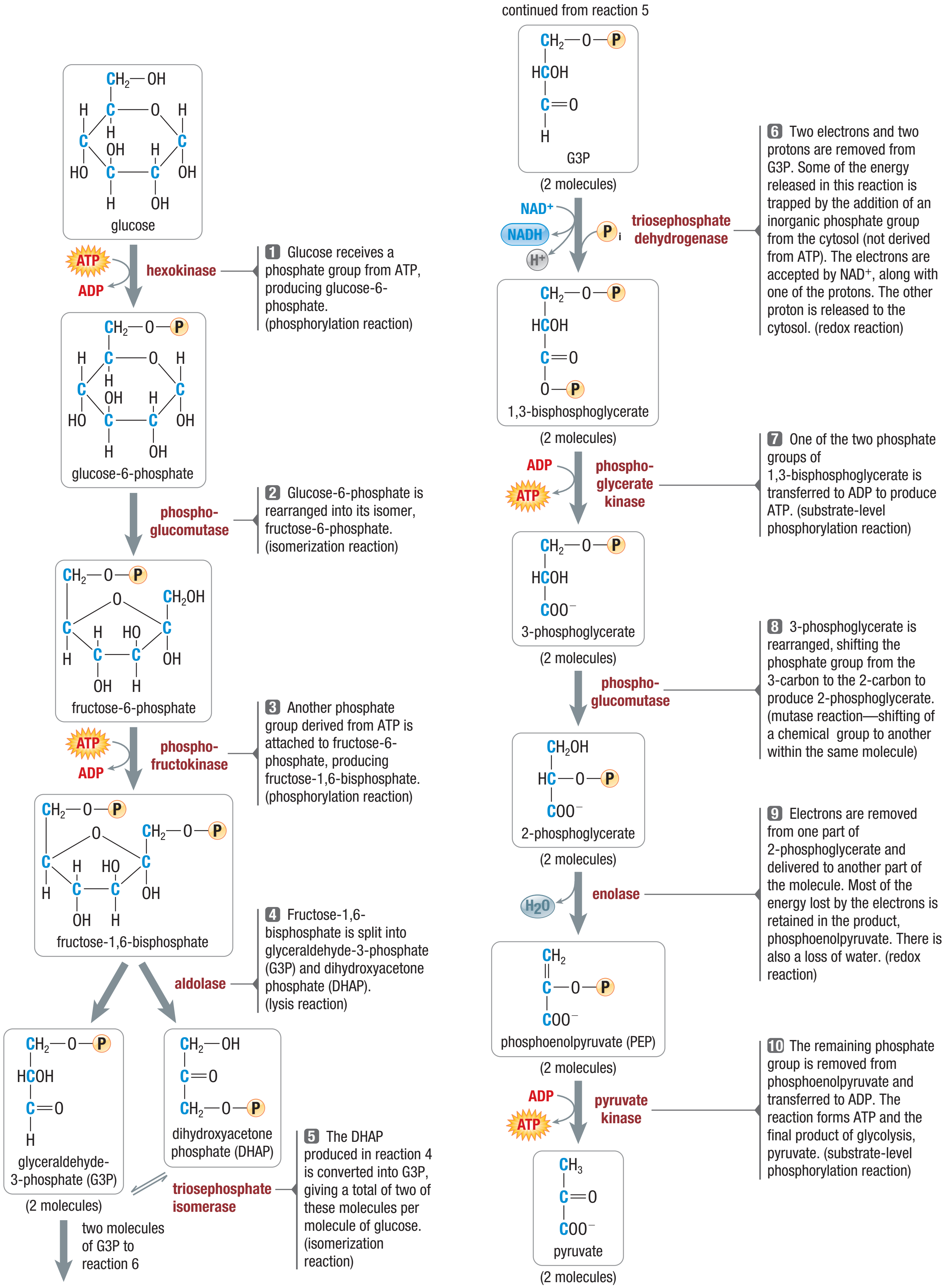


Figure 1 Summary of glycolysis showing the energy inputs and outputs



1 Glucose receives a phosphate group from ATP, producing glucose-6-phosphate. (phosphorylation reaction)

2 Glucose-6-phosphate is rearranged into its isomer, fructose-6-phosphate. (isomerization reaction)

3 Another phosphate group derived from ATP is attached to fructose-6-phosphate, producing fructose-1,6-bisphosphate. (phosphorylation reaction)

4 Fructose-1,6-bisphosphate is split into glyceraldehyde-3-phosphate (G3P) and dihydroxyacetone phosphate (DHAP). (lysis reaction)

5 The DHAP produced in reaction 4 is converted into G3P, giving a total of two of these molecules per molecule of glucose. (isomerization reaction)

6 Two electrons and two protons are removed from G3P. Some of the energy released in this reaction is trapped by the addition of an inorganic phosphate group from the cytosol (not derived from ATP). The electrons are accepted by NAD^+, along with one of the protons. The other proton is released to the cytosol. (redox reaction)

7 One of the two phosphate groups of 1,3-bisphosphoglycerate is transferred to ADP to produce ATP. (substrate-level phosphorylation reaction)

8 3-phosphoglycerate is rearranged, shifting the phosphate group from the 3-carbon to the 2-carbon to produce 2-phosphoglycerate. (mutase reaction—shifting of a chemical group to another within the same molecule)

9 Electrons are removed from one part of 2-phosphoglycerate and delivered to another part of the molecule. Most of the energy lost by the electrons is retained in the product, phosphoenolpyruvate. There is also a loss of water. (redox reaction)

10 The remaining phosphate group is removed from phosphoenolpyruvate and transferred to ADP. The reaction forms ATP and the final product of glycolysis, pyruvate. (substrate-level phosphorylation reaction)

Figure 2 The reactions of glycolysis, including the initial five-step energy investment phase followed by the five-step energy payoff phase. Because two molecules of G3P are produced in reaction 5, all the reactions from 6 to 10 are doubled (not shown). The names of the enzymes that catalyze each reaction are in red.

As you look at Figures 1 and 2, there are three key points to keep in mind:

1. Initially, 2 ATP are consumed as glucose and fructose-6-phosphate become phosphorylated. In the energy investment phase, 2 ATP increase the free energy of the chemicals in the glycolytic pathway. However, even more free energy is released in the payoff phase, as 4 ATP and 2 NADH molecules are synthesized.
2. Besides yielding a net of 2 ATP and 2 NADH for each molecule of glucose that is oxidized, no carbon is lost. All six carbons in glucose are accounted for in the two molecules of pyruvate. However, since glucose has been partially oxidized, the potential energy in two molecules of pyruvate is less than the potential energy in one molecule of glucose. Although two water molecules were produced in Step 9, they are not usually included in the overall equation for glycolysis because they are later consumed in the hydrolysis of the 2 ATP molecules and the reforming of 2 ADP and 2 P_i.
3. During glycolysis, ATP is produced using substrate-level phosphorylation (**Figure 3**). In this mode of ATP synthesis, an enzyme transfers a phosphate group from a high-energy substrate molecule to adenosine diphosphate (ADP), producing ATP. Substrate-level phosphorylation is also the mode of ATP synthesis that is used during the citric acid cycle.

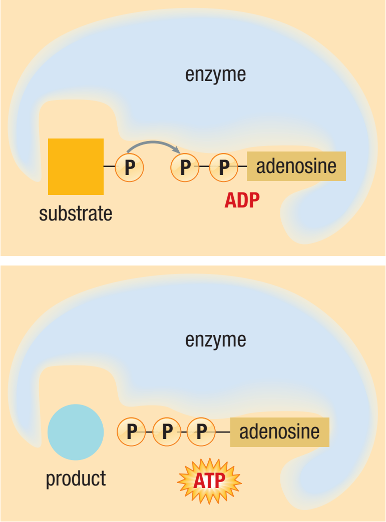


Figure 3 During substrate-level phosphorylation, a phosphate group is transferred from a high-energy donor directly to ADP, forming ATP.

The net equation for glycolysis is given below:

$$\text{glucose} + 2\ \text{ADP} + 2\ \text{P}_i + 2\ \text{NAD}^+ \rightarrow 2\ \text{pyruvate} + 2\ \text{ATP} + 2\ \text{NADH} + 2\text{H}^+$$

The energy that is stored by the synthesis of two moles of ATP is 62 kJ. The energy that could be released by the complete oxidation of one mole of glucose is 2870 kJ. The glycolysis energy conversion efficiency (per mole of glucose processed) can be represented as follows:

$$\text{energy conversion efficiency} = \frac{62\ \text{kJ}}{2870\ \text{kJ}} \times 100\ \% = 2.2\ \%$$

For every one mole of glucose, only about 2.2 % of the available free energy is converted to ATP in glycolysis. Some of the energy is lost as thermal energy, but most is still stored in two pyruvate molecules and two NADH molecules, which will continue through the subsequent stages of aerobic respiration. Different organisms use a variety of methods to transfer the NADH (or the electrons it carries) into the mitochondria and to the electron transport chain. These methods vary in their energy cost, so the amount of ATP generated for each NADH formed in glycolysis can vary. Though the percentage return for glycolysis is low, some organisms use glycolysis as their primary source of energy. For aerobic organisms, however, this is just the beginning process.

Pyruvate Oxidation and the Citric Acid Cycle

The two molecules of pyruvate that are synthesized by glycolysis still contain approximately 75 % of the energy found in one molecule of glucose. The extraction of the remaining free energy in pyruvate continues via pyruvate oxidation and the citric acid cycle (**Figure 4**, next page). In these reactions, more ATP and more of the electron carriers NADH and $FADH_2$ are formed, while the remaining glucose is completely oxidized. Carbon is released in the form of waste CO_2.

Pyruvate Oxidation

The reactions of the citric acid cycle occur in the mitochondrial matrix, so the pyruvates that are produced in glycolysis must pass through both the outer and inner mitochondrial membranes. Large pores in the outer membrane allow pyruvate to diffuse through. For pyruvate to cross the inner membrane, however, a pyruvate-specific membrane carrier is required. Once pyruvate enters the matrix, it is converted into an acetyl group, which is then temporarily bonded to a sulfur atom on the end of a large molecule called coenzyme A, or CoA. The result is an acetyl-CoA complex. This multistep process is referred to as pyruvate oxidation (or pyruvic acid oxidation).

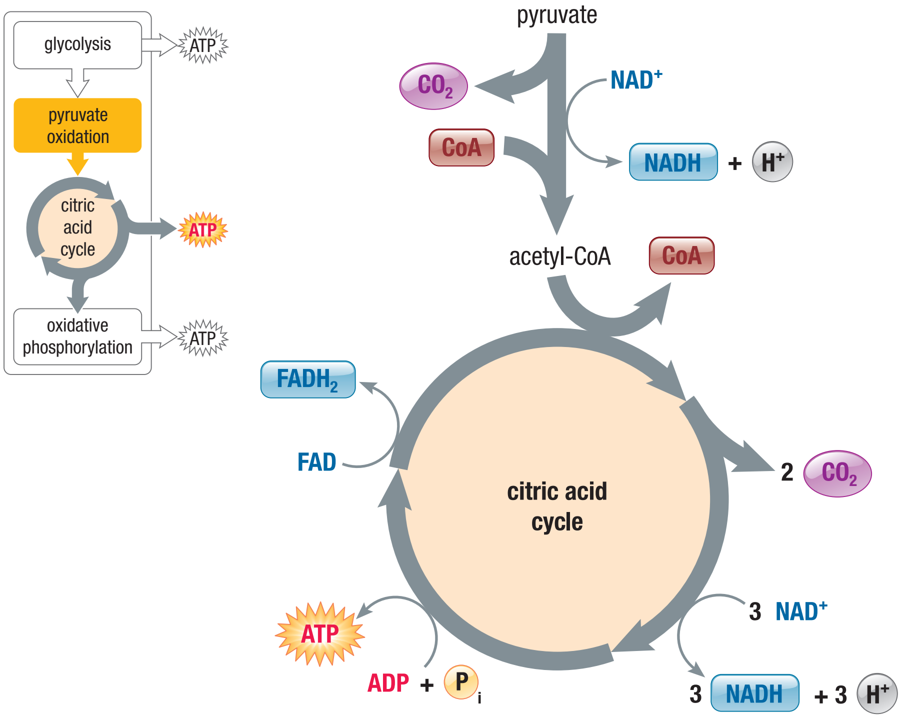


Figure 4 The overall reactions of pyruvate oxidation and the citric acid cycle

The conversion of pyruvate to acetyl-CoA starts with a **decarboxylation reaction** in which the carboxyl ($-COO^-$) group of pyruvate is removed and forms a CO_2 as a waste product (**Figure 5**). In fact, this reaction produces one-third of the CO_2 that we exhale! Decarboxylation is followed by oxidation of the remaining two carbon molecules, producing an acetyl group. This **dehydrogenation** reaction transfers two electrons and a proton to NAD^+, forming NADH, and releases an H^+ ion into solution. Lastly, the acetyl group reacts with the sulfur atom of coenzyme A, forming the high-energy intermediate acetyl-CoA. The net reaction for pyruvate oxidation can be represented as follows:

$$2 \text{ pyruvate} + 2\,NAD^+ + 2\,CoA \rightarrow 2 \text{ acetyl-CoA} + 2\,NADH + 2\,H^+ + 2\,CO_2$$

decarboxylation reaction a chemical reaction that removes a carboxyl group to form CO_2

dehydrogenation the removal of a hydrogen atom from a molecule

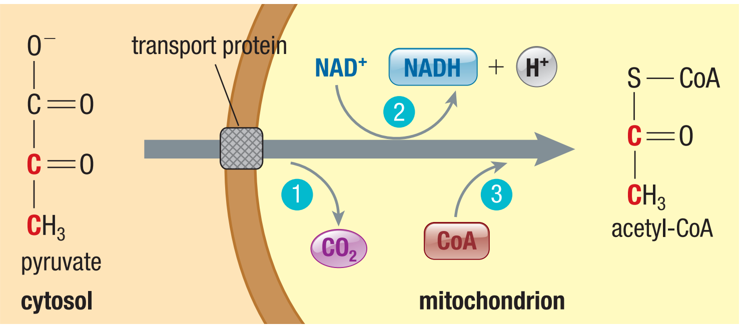
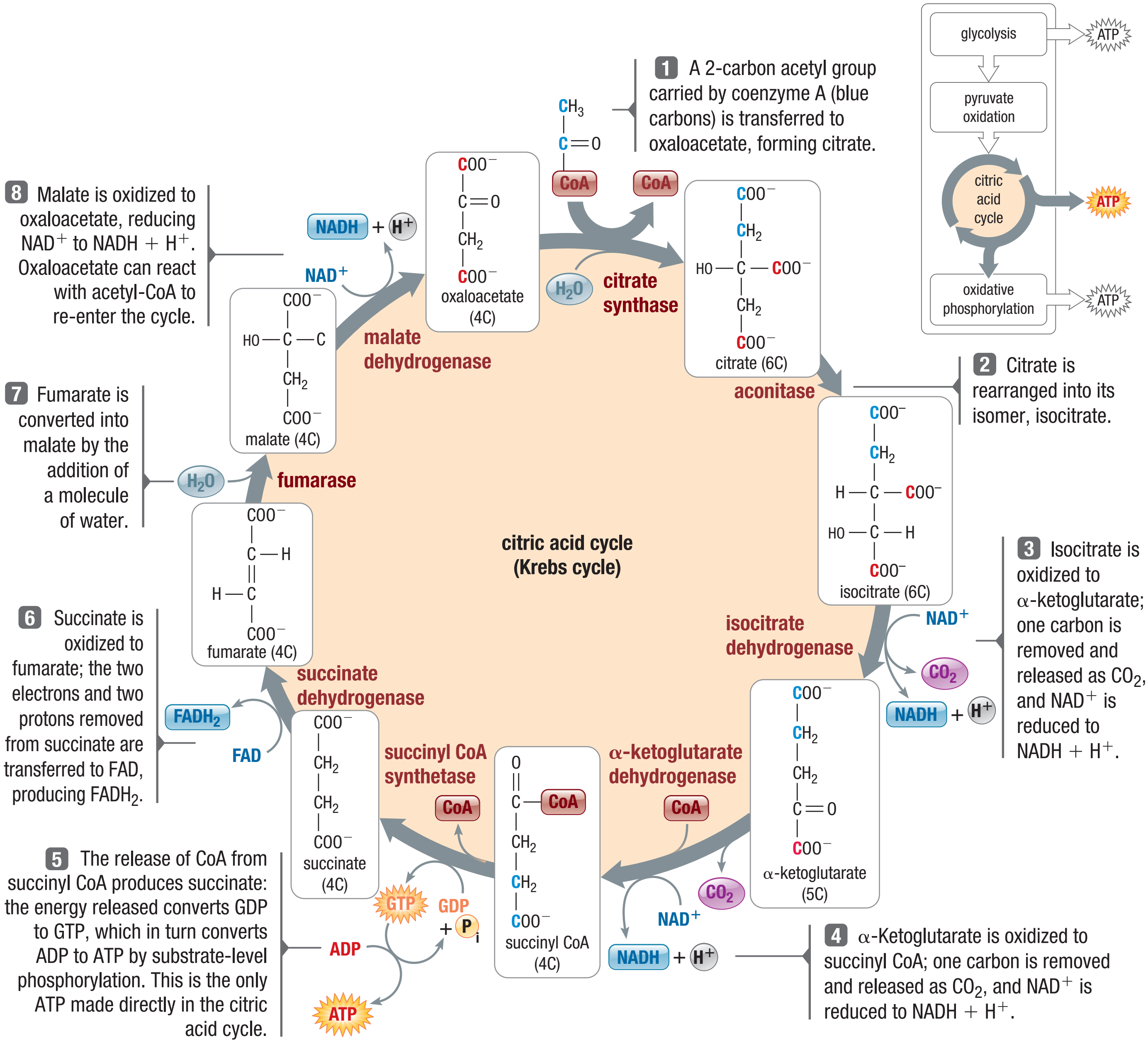


Figure 5 In the mitochondrion, pyruvate is oxidized to an acetyl group, which is carried to the citric acid cycle by CoA. The reactions that are catalyzed by the pyruvate dehydrogenase complex include (1) decarboxylation, followed by (2) a dehydrogenation, and finally (3) a reaction with coenzyme A (CoA) that produces acetyl-CoA. Note that the sulfur atom (S) is part of coenzyme A.

The Citric Acid Cycle

In 1937, Sir Hans Krebs (1900–1981), a biochemist at the University of Sheffield in England, discovered the metabolic reactions that became known as the Krebs cycle (now called the citric acid cycle). The citric acid cycle consists of eight enzyme-catalyzed reactions. Seven of these reactions take place in the mitochondrial matrix, and one binds to the matrix side of the inner mitochondrial membrane. Combined, these reactions result in the oxidization of acetyl groups to CO_2, accompanied by the synthesis of ATP, NADH, and another nucleotide-based molecule, flavin adenine dinucleotide (FAD; the reduced form is $FADH_2$) (**Figure 6**). For each acetyl-CoA that enters the citric acid cycle, three NADH and one $FADH_2$ are produced, along with one ATP that is synthesized by substrate-level phosphorylation. In a complete turn of the cycle, one 2-carbon acetyl unit is consumed and two CO_2 molecules are released, thereby completing the conversion of all the carbon atoms that were originally in glucose into CO_2. The CoA molecule that carried the acetyl group to the cycle is released and again participates in pyruvate oxidation to pick up another acetyl group. The net reactants and products of one turn of the citric acid cycle are given below:

$$\text{acetyl-CoA} + 3\,\text{NAD}^+ + \text{FAD} + \text{ADP} + \text{P}_i \rightarrow$$
$$2\,\text{CO}_2 + 3\,\text{NADH} + 3\,\text{H}^+ + \text{FADH}_2 + \text{ATP} + \text{CoA}$$



1 A 2-carbon acetyl group carried by coenzyme A (blue carbons) is transferred to oxaloacetate, forming citrate.

2 Citrate is rearranged into its isomer, isocitrate.

3 Isocitrate is oxidized to α-ketoglutarate; one carbon is removed and released as CO_2, and NAD^+ is reduced to $NADH + H^+$.

4 α-Ketoglutarate is oxidized to succinyl CoA; one carbon is removed and released as CO_2, and NAD^+ is reduced to $NADH + H^+$.

5 The release of CoA from succinyl CoA produces succinate: the energy released converts GDP to GTP, which in turn converts ADP to ATP by substrate-level phosphorylation. This is the only ATP made directly in the citric acid cycle.

6 Succinate is oxidized to fumarate; the two electrons and two protons removed from succinate are transferred to FAD, producing $FADH_2$.

7 Fumarate is converted into malate by the addition of a molecule of water.

8 Malate is oxidized to oxaloacetate, reducing NAD^+ to $NADH + H^+$. Oxaloacetate can react with acetyl-CoA to re-enter the cycle.

Figure 6 The reactions in the citric acid cycle: Enzyme names are in red. The CoA that is released in reaction 1 can cycle back for another turn of pyruvate oxidation.

During glycolysis, one molecule of glucose is converted into two molecules of pyruvate. Then, during pyruvate oxidation, each molecule of pyruvate is converted into one acetyl group. Therefore, all of the reactants and products are doubled when the citric acid cycle is considered as a continuation of glycolysis and pyruvate oxidation. Review Figure 6 as you consider the citric acid cycle:

- Two acetyl-CoA molecules enter the citric acid cycle from glycolysis and the pyruvate oxidation of one glucose molecule.
- In Step 1, the acetyl group enters the cycle as it reacts with oxaloacetate to form one molecule of citrate. This is why the process is called the citric acid cycle.
- In Steps 3, 4, 5, 6, and 8, some of the released energy is captured and used to form NADH, ATP, and $FADH_2$.
- In Steps 3, 4, and 8, NAD^+ is reduced to form NADH.
- Step 5 produces ATP from ADP and P_i by substrate-level phosphorylation.
- Step 6 reduces FAD to form $FADH_2$.
- Because one glucose molecule yields two pyruvate molecules, each glucose molecule generates two turns of the citric acid cycle.

By the end of the citric acid cycle, the original glucose molecule has been completely dismantled. The original carbon and oxygen atoms are in the form of CO_2 and are released as waste. All that remains of the original glucose molecule are the hydrogens, which are now carried by NADH and $FADH_2$. The electrons associated with these hydrogens retain a large amount of chemical potential energy.

Investigation 4.2.1

Observing the Products of Cellular Respiration (p. 199)

In this investigation, you will design an experiment that compares the rate of energy consumption before, during, and after exercise.

Mini Investigation

Observing Evidence of Respiration

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A1, A2.1**

In this investigation, you will analyze the results of exhaling CO_2 to make a direct connection between pyruvate oxidation and the citric acid cycle—the source of all exhaled carbon dioxide. Keep in mind that CO_2 forms carbonic acid when it reacts with water. The following chemical equation represents the formation of carbonic acid, H_2CO_3, from CO_2 and water:

$$CO_2(g) + H_2O(l) \leftrightarrow H^+(aq) + H_2CO_3^-(aq)$$

Equipment and Materials: drinking straw; limewater; slightly basic solution (0.01 mol/L NaOH); phenolphthalein indicator

Do not inhale through the straw. Do not share straws.

Sodium hydroxide solution is corrosive. Avoid skin and eye contact. If sodium hydroxide comes in contact with your skin or eyes, wash the affected area for 15 min with cool water and notify your teacher.

Phenolphthalein indicator is flammable. Keep it away from open flames.

1. Take a deep breath, and then slowly exhale the entire breath out the drinking straw into a small flask with limewater.
2. Repeat Step 1 until you observe a marked change in the limewater solution.
3. Observe the change in the limewater solution over time. Record how many breaths it took to observe a change in the limewater solution.
4. Repeat Steps 1 to 3, but now exhale into a slightly basic solution containing phenolphthalein indicator.

A. What happened to the limewater as you exhaled through the straw? Why? T/I

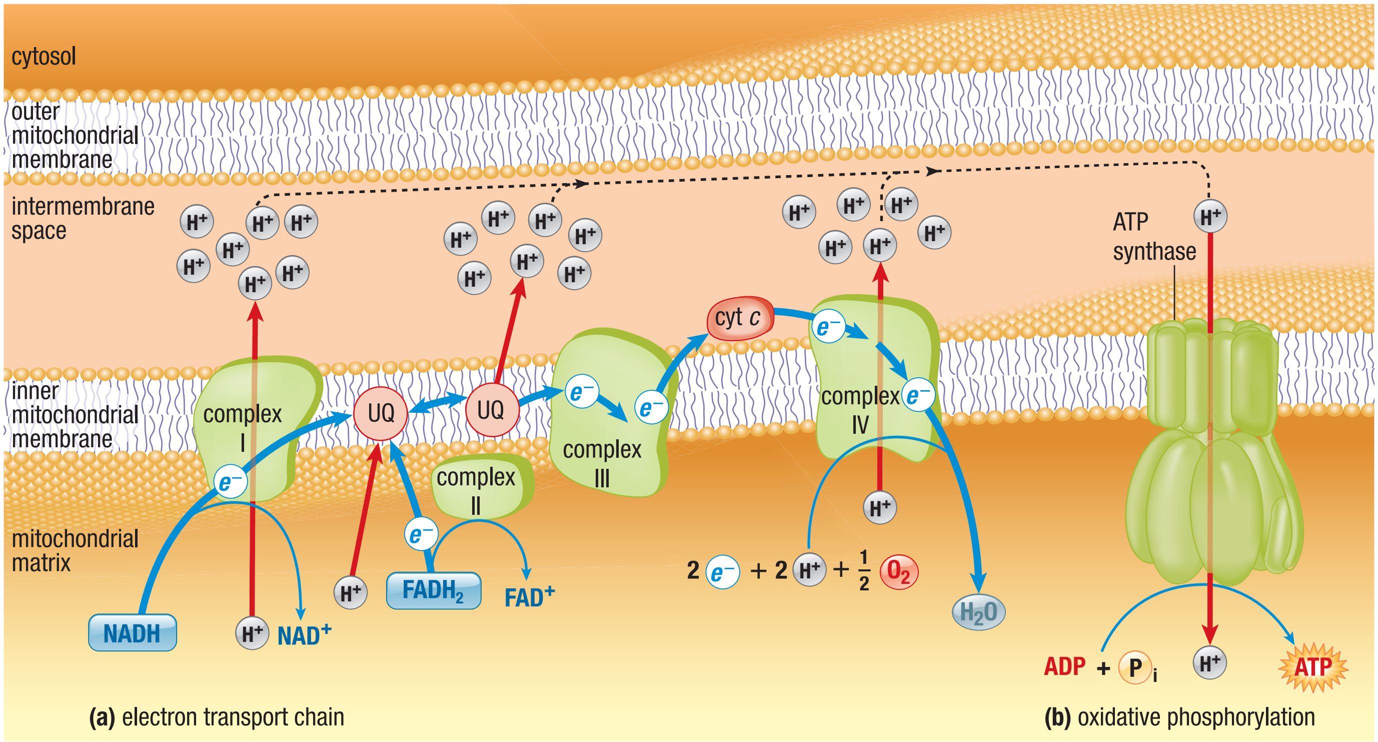
B. What happened to the phenolphthalein indicator as you exhaled CO_2 into the slightly basic solution? Why? T/I

The Electron Transport Chain and Chemiosmosis

In the citric acid cycle, all the carbon that was present in glucose was oxidized and released as CO_2. In addition, while some ATP was formed by substrate-level phosphorylation, most of the potential energy that was originally present in glucose was captured during the formation of NADH and $FADH_2$. The electron transport chain extracts the potential energy in these molecules and makes it available for the synthesis of additional ATP.

The Electron Transport Chain

The electron transport chain comprises a system of components that, in eukaryotes, occurs on the inner mitochondrial membrane (**Figure 7(a)**). This chain facilitates the transfer of electrons from NADH and $FADH_2$ to O_2. It consists of four protein complexes: complex I, NADH dehydrogenase; complex II, succinate dehydrogenase; complex III, cytochrome complex; and complex IV, cytochrome oxidase. Complex II is a single peripheral membrane protein, whereas the other three complexes are composed of multiple proteins.



(a) electron transport chain

(b) oxidative phosphorylation

Figure 7 (a) During the electron transport chain, electrons flow through a series of proton (H^+) pumps. The energy released builds an H^+ gradient across the inner mitochondrial membrane. (b) During oxidative phosphorylation, ATP synthase catalyzes ATP synthesis using energy from the H^+ gradient across the membrane (chemiosmosis).

The flow of electrons from one complex to another is facilitated by two mobile electron shuttles. Ubiquinone (UQ), which is a hydrophobic molecule found in the core of the membrane, shuttles electrons from complexes I and II to complex III. A second shuttle, cytochrome *c* (cyt *c*), is located on the intermembrane space side of the membrane and transfers electrons from complex III to complex IV.

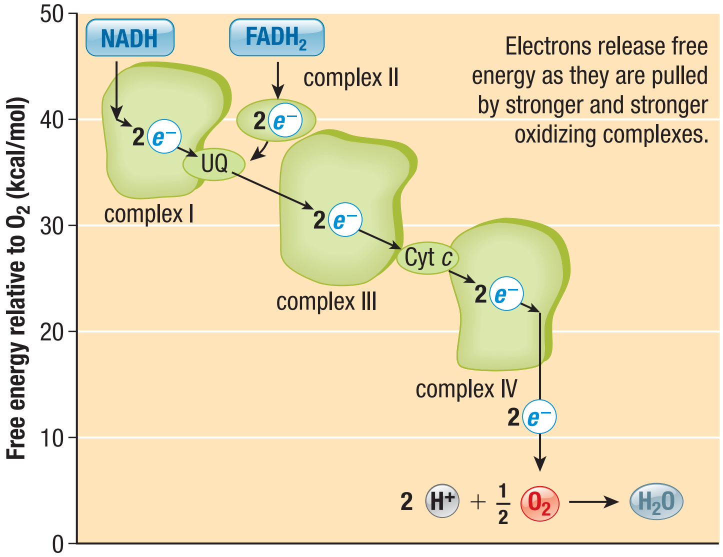
THE DRIVING FORCE BEHIND ELECTRON TRANSPORT

Complexes I, III, and IV are protein complexes with increasing electronegativity along the chain. These complexes have cofactors that alternate between reduced and oxidized states as they pull electrons from upstream molecules and subsequently donate electrons to more electronegative downstream molecules. Thus, it is not the proteins themselves that transfer electrons, but rather non-protein groups bound to the proteins of each complex. The electron transport chain is the final destination of all the oxygen we breathe, which is transported around the body. Oxygen goes to the mitochondria to perform the single vital task of pulling electrons away from complex IV.

Before oxygen removes electrons from complex IV, all the carriers and NADH are fully reduced, with stable, full electron shells. Nothing can happen due to their stable state. For example, NADH cannot have its electrons removed by complex I because complex I already has a full complement of electrons. However, oxygen is highly electronegative. When oxygen interacts with complex IV, it removes a pair of electrons.

As an oxygen atom removes two electrons from complex IV, it also reacts with two protons (2 H^+) from the matrix to form a single molecule of water. In total, then, for every O_2 gas molecule we breathe in, four electrons are pulled through the electron transport chain and two water molecules are produced. This triggers a chain reaction. Complex IV cannot get the electrons back from oxygen (which has a stronger pull), but it is in contact with the slightly weaker (less electronegative) complex III. It takes two electrons away from complex III, which, in turn, takes electrons away from complex I. This cascade of events continues along the chain and is very fast—almost instantaneous.

The electrons are being pulled by forces of attraction through the chain, beginning with O_2, which has the highest electronegativity. The electronegative nature of O_2 drives the entire process of the electron transport chain. The individual electron carriers of the chain are, in fact, organized in a very specific way, from high to low free energy (**Figure 8**). Each component is more electronegative than the preceding carrier in the chain. Oxygen has the strongest pull on electrons, and NADH has the weakest pull. Overall, molecules such as NADH contain an abundance of free energy and can be readily oxidized, whereas O_2, the terminal electron acceptor of the chain, is strongly electronegative. The electrons in NADH have the most free energy. This energy is released as they form stronger and stronger bonds, moving through the electron transport chain (bond formation releases energy).



Electrons release free energy as they are pulled by stronger and stronger oxidizing complexes.

Figure 8 Redox components of the electron transport chain are organized from high to low energy. Without the driving force of oxygen, the entire chain would stop.

Mini **Investigation**

Modelling the Oxidation Shuffle

Skills: Questioning, Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1**

This investigation will help you understand how and why the electron transport chain (ETC) works and what conditions can stop it from moving forward.

Equipment and Materials: 10 balls (representing electrons); 7 team members (1 helper and 6 "chemicals" representing 1 NADH, 4 electron transport chain complexes, and 1 oxygen atom); 6 oxidation strength cards

1. Six students stand in a straight line, facing forward, with the NADH student on the left end and the oxygen student on the right end. The four students in the middle represent ETC complexes.
2. The helper hands the NADH and ETC students two electrons (balls) each. They place one electron in each hand. The oxygen student is not given any electrons.
3. Then the helper passes out the oxidation strength cards. The higher the number on the card, the greater is the ability of the complex to replace any missing electrons (the greater its electronegativity). NADH is always given card number 1 (the weakest oxidizer). Oxygen is always given card number 6 (the strongest oxidizer). The other four cards are shuffled and given to the four remaining students at random. Record the order of the cards; for example, 1, 3, 4, 2, 5, 6.

4. In this simulation, any student who is missing two electrons or has just lost two electrons can take two electrons from a student standing immediately next to them, but ONLY if the oxidation strength of the next student is less than theirs.
5. The simulation will always begin when the oxygen student takes two electrons from the student standing next to them.
6. As long as any student without electrons has a greater oxidation strength than an adjacent student, electron transfer can happen.
7. Continue acting out the electron transport reactions until a student cannot replace their lost electrons. When this happens, the trial ends.
8. Record the position of the student with the missing electrons. Was it the NADH student?
9. Repeat Steps 1 to 8, being sure to reshuffle the cards for the four middle students.
10. Continue to conduct new trials of the simulation until a trial ends with the removal of electrons from NADH.

A. Explain what order(s) of cards allowed the complete electron transport from NADH to oxygen. T/I

B. How does this investigation model the protein complexes in the electron transport chain? T/I

C. In glycolysis and the citric acid cycle, which molecules obtain electrons? Where did these electrons originally come from? T/I

D. Can the electrons ever move along the chain without oxygen? T/I

E. What might happen to the chain if there were no source of NADH? T/I

F. What happens to NADH after it loses electrons? T/I

G. In a modified version of this simulation, oxygen atoms continuously arrive at the end of the transport chain, while NADH molecules continuously lose electrons at the other end but get “replacements” from a large container. In aerobic cellular respiration pathways, what would this large container represent? T/I

Chemiosmosis

Although the end result of aerobic cellular respiration is the synthesis of ATP, electron transport from NADH or $FADH_2$ to O_2 does not, in itself, produce any ATP. To understand how ATP is formed from electron transport, go back to Figure 7. Recall that NADH has more free energy than O_2. During electron transport, the free energy that is released is used to do work, specifically the work of transporting protons (H^+ ions) across the inner mitochondrial membrane, from the matrix into the intermembrane space. As a result of proton pumping across the inner membrane, the H^+ concentration in the intermembrane space becomes much higher than the H^+ concentration in the matrix. This difference in H^+ concentration is called a **proton gradient**, and it is a form of potential energy.

proton gradient a difference in proton (H^+ ion) concentration across a membrane

Electron flow through the electron transport chain drives a series of proton pumps in the inner mitochondrial membrane. Within complexes I and IV, specific protein components use the energy that is released from electron transport for proton pumping. In addition, as ubiquinone molecules (UQ) accept electrons from complexes I and II, they pick up protons from the matrix. After migrating through the membrane and donating electrons to complex III, ubiquinone retains a neutral charge by releasing protons into the intermembrane space.

When one side of the inner mitochondrial membrane has more protons than the other side, the difference represents a source of energy that can be harnessed to do work. The potential energy that is possessed by a proton gradient is derived from two factors. First, a chemical gradient exists across the membrane because the concentration of protons on both sides is not equal. Second, because the protons are charged, they repel each other and are attracted to the more negative interior of the matrix. The combination of a concentration gradient and an electrical potential (charge) gradient across the membrane produces a force known as the **proton-motive force.**

proton-motive force a force that moves protons because of a chemical gradient (often referred to as an electrochemical gradient) of protons across a membrane

The ability of cells to use the proton-motive force to do work is called **chemiosmosis**. It was first proposed as a mechanism to generate ATP by the British biochemist Peter Mitchell, who received a Nobel Prize in Chemistry in 1978. In mitochondria, the energy for chemiosmosis comes from the oxidation of energy-rich molecules, such as NADH, by the electron transport chain. Chemiosmosis also accounts for the generation of ATP in chloroplasts, where electron transport is driven by light energy. Chemiosmosis, however, does not only refer to the synthesis of ATP.

chemiosmosis a process in which ATP is synthesized using the energy of an electrochemical gradient and the ATP synthase enzyme

The proton-motive force is also used to pump substances across membranes and to drive the rotation of flagella in prokaryotes.

This mode of ATP synthesis, which is linked to the oxidation of energy-rich molecules by an electron transport chain, is called oxidative phosphorylation. Unlike substrate-level phosphorylation, which occurs during glycolysis and the citric acid cycle, oxidative phosphorylation relies on the action of a large multi-protein complex called ATP synthase.

ATP SYNTHASE: A MOLECULAR MOTOR

ATP synthase is a structure that spans the inner mitochondrial membrane. It consists of a basal unit that is embedded in the inner mitochondrial membrane and connected to a headpiece by a stalk (**Figure 7(b)**, page 178). The headpiece extends into the mitochondrial matrix. The basal unit forms a channel through which H^+ ions can pass freely. The proton-motive force moves protons in the intermembrane space through the channel in the enzyme's basal unit, down their concentration gradient, and into the matrix. The flow of protons powers ATP synthesis by the headpiece. Evidence indicates that the binding of three protons to sites in the headpiece causes the headpiece to rotate in a way that catalyzes the formation of one ATP molecule from ADP and P_i. The rotating of the headpiece of ATP synthase represents the smallest molecular rotary motor known in nature.

In Chapter 2, you learned about active transport pumps that use the energy created by the hydrolysis of ATP to ADP and P_i to transport ions across membranes against their concentration gradients. An active transport pump is, in fact, an ATP synthase that is operating in reverse. It does not synthesize ATP but rather uses the free energy from the hydrolysis of ATP to provide the energy needed to pump ions (such as protons) across a membrane. The ability to harness the potential energy that is present in a proton gradient to synthesize ATP is fundamental to almost all forms of life and is developed early in the evolution of life. This is shown, in part, by the fact that the structure and function of the ATP synthase complex in mitochondria are essentially identical to those in the thylakoid membrane of the chloroplast and the plasma membrane of prokaryotic cells.

Uncoupling Electron Transport and Chemiosmosis

During oxidative phosphorylation, the potential energy that is released by the oxidation of NADH is used to pump protons into the intermembrane space and build up the proton-motive force. When electron transport and ATP synthesis are uncoupled, the energy that is released during electron transport is not converted to ATP energy. Instead, it is released as thermal energy when protons rush back across the inner membrane without passing through ATP synthase. One way that the uncoupling is achieved is through regulating the expression of a number of uncoupling proteins. Uncoupling proteins, when present, are in the inner mitochondrial membrane and give protons an alternative pathway to re-enter the matrix—a pathway that does not produce ATP and instead releases thermal energy. Certain tissues, such as brown adipose fat, contain mitochondria in which the expression of uncoupling proteins is particularly high. The thermal energy that is generated by these tissues is important for the maintenance of body temperature in hibernating mammals (**Figure 9**), birds that need excess thermal energy in very cold environments, and very young offspring, including human infants. Uncoupling electron transport causes free energy that would be used to generate ATP to be released as thermal energy and maintain body temperature instead.

Figure 9 Bears are able to hibernate because cells in some of their tissues can uncouple the electron transport chain and chemiosmosis to produce thermal energy.

Several chemical compounds, called ionophores, can also act as uncouplers because they form channels across membranes through which ions, including protons, can leak. Because these compounds allow for high rates of electron transport but reduce ATP synthesis, they are potentially toxic. One such chemical, 2,4-dinitrophenol (DNP), was used in diet pills in the 1930s. Ingesting DNP reduces the rate of production of ATP, and cells respond by consuming stored fat more rapidly. Although DNP was effective for losing weight, it had many harmful side effects, including overheating, and its use was discontinued after only a few years. Any chemical may have serious effects if it is capable of influencing aerobic respiration and ATP production.

4.2 Review

Summary

- Glycolysis extracts energy from sugar molecules and produces ATP.
- Pyruvate oxidation converts two pyruvate molecules into two acetyl-CoA molecules, NADH, H^+, and CO_2 waste.
- The citric acid cycle consists of eight enzyme-catalyzed reactions. It uses acetyl-CoA to produce energy, in the form of NADH, $FADH_2$, and ATP, and release CO_2.
- The electron transport chain extracts the potential energy from NADH and $FADH_2$ and converts it to ATP.
- Chemiosmosis is the process of pumping protons across the inner mitochondrial membrane, creating a proton-motive force that provides the energy used to produce ATP.
- Harnessing the potential energy that is present in a proton gradient to synthesize ATP is fundamental to almost all forms of life and is developed early in the evolution of life.
- Uncoupling electron transport and the synthesis of ATP can be caused by making the inner mitochondrial membrane permeable to protons. The energy that is released during electron transport is then converted to thermal energy.

Questions

1. Why is glycolysis considered to be the most fundamental and probably the most ancient of all metabolic pathways? K/U
2. How efficient is glycolysis at converting glucose to ATP? Are there other high-energy products of glycolysis? K/U
3. Glycolysis, pyruvate oxidation, and the citric acid cycle produce only a small amount of ATP from the energy in a glucose molecule. In what form(s) is (are) the rest of the harvestable energy that is converted to ATP in the electron transport chain and chemiosmosis? K/U T/I
4. How does the electron transport chain produce ATP? What is the driving force? K/U
5. (a) Do the electrons in NADH have the most or the least free energy in the electron transport chain?
   (b) The electrons in NADH form bonds as they move through the electron transport chain. Do these bond formations use or release energy? K/U T/I
6. Which stages of aerobic cellular respiration occur in the mitochondria, and which stages do not? K/U
7. Write the overall chemical equation for each process. K/U
   (a) glycolysis
   (b) pyruvate oxidation
   (c) citric acid cycle
8. What important molecule is needed for oxidative phosphorylation but not needed for substrate-level phosphorylation? K/U
9. What is the primary function of the proton-motive force? K/U
10. Give an example of how uncoupling is used by organisms to increase survival. K/U
11. Research the applications of ionophores. How and why are they used in the cattle industry? 🌐 T/I
12. The oxygen gas that animals breathe in is necessary to drive the electron transport chain and generate ATP, but it also undergoes a chemical reaction to produce a particular product. K/U T/I
    (a) What is the product?
    (b) For every mole of oxygen molecules you breathe in, how many moles of this product are formed?
    (c) How might this be of benefit to desert animals?

🌐 WEB LINK

The Efficiency and Regulation of Cellular Respiration

4.3

In this section, you will calculate the efficiency of aerobic cellular respiration as it extracts the energy from a molecule of glucose. As well, you will learn how this entire multi-enzyme pathway is regulated so that it remains flexible and responsive to changing cellular demands for ATP and changes in food supply.

The Efficiency of Cellular Respiration

Determining the total number of ATP molecules that are synthesized for each molecule of glucose that is oxidized is an important exercise that incorporates all parts of the respiration pathway. The efficiency of oxidative phosphorylation is difficult to calculate. Remember that electron transport and oxidative phosphorylation are distinct processes that are not always completely coupled to each other. Research suggests that for each NADH that is oxidized, and therefore for each pair of electrons that travels down the electron transport chain, 10 H^+ are pumped into the inner membrane space. Scientists also know that 3 or 4 H^+ are needed to flow back through the ATP synthase for the synthesis of each molecule of ATP. Therefore, at most, 3 ATP are made for every NADH oxidized by the electron transport chain. Because the oxidation of $FADH_2$ bypasses the proton-pumping complex I (Section 4.2), it does not lead to as many protons being pumped across the membrane. Thus, for each $FADH_2$ oxidized, only about two molecules of ATP are synthesized.

Now we can act as accountants and work out the maximum ATP yield for the entire aerobic cellular respiration pathway. Given the complete oxidation of one molecule of glucose to CO_2 and H_2O, and assuming that the entire H^+ gradient produced by electron transfer is used for ATP synthesis (**Figure 1**, next page), a total of 10 NADH, 10 H^+, and 2 $FADH_2$ from glycolysis, pyruvate oxidation, and the citric acid cycle are oxidized by the electron transport chain.

As noted in Section 4.2, because the NADH that is produced during glycolysis is in the cytosol, it does not have immediate access to the electron transport chain within mitochondria. To overcome this problem, cells use one of two "shuttle" systems that transfer the high-energy electrons from NADH across the inner mitochondrial membranes and into the matrix. In one such system, called the malate-aspartate shuttle, the transfer is very energy efficient and is used by many cells. The NADH in the cytosol is oxidized to NAD^+, and the electrons are transferred across the membrane and used to reduce an NAD^+ to NADH within the matrix. An alternative pathway, called the glycerol-phosphate shuttle, involves the transfer of electrons across the membrane from NADH to FAD in the matrix. This results in the formation of $FADH_2$, which has less free energy. Cells that use this system generate the equivalent of 2, rather than 3, ATP for every NADH produced in glycolysis. For cells that use the more efficient malate-aspartate shuttle, electron transport and oxidative phosphorylation produce 34 ATP from NADH and $FADH_2$:

$$10\ \text{NADH} \times 3\ \text{ATP} = 30\ \text{ATP}$$

$$2\ \text{FADH}_2 \times 2\ \text{ATP} = 4\ \text{ATP}$$

The total maximum ATP produced per glucose molecule oxidized in cellular respiration can be added as follows:

glycolysis	2 ATP
citric acid cycle	2 ATP
electron transport	34 ATP
total	38 ATP

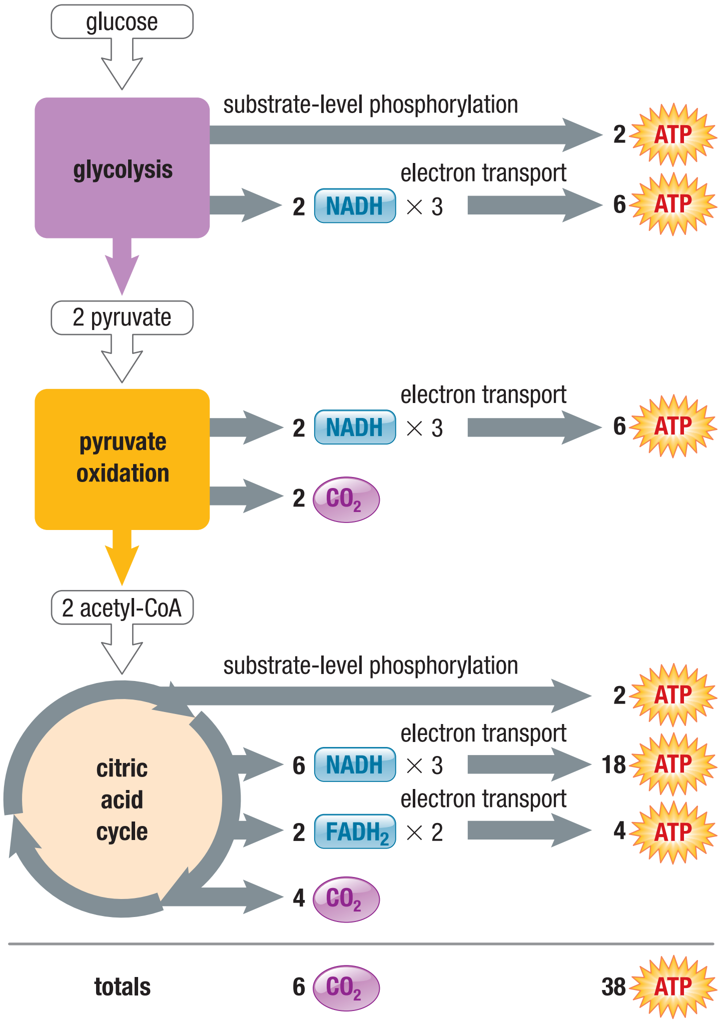


Figure 1 Total ATP yield by aerobic cellular respiration from the complete oxidation of one molecule of glucose. This tally assumes an energy-efficient transfer of energy from all NADH to the electron transport chain, including the use of the malate-aspartate shuttle.

This calculation assumes a maximum yield of ATP. There are several reasons why the total yield might be less than 38 ATP. You have already learned about the inexact NADH and $FADH_2$ to ATP ratio. In addition, energy from H^+ flow may be lost due to uncoupling proteins or used for other mitochondrial processes, as well as the process that produces ATP (such as powering the mitochondria's uptake of pyruvate). Also, cells that use a glycerol-phosphate shuttle system produce 2 fewer ATPs per glucose.

How efficient is aerobic respiration at extracting the energy from glucose and converting it into ATP? The hydrolysis of ATP to ADP and P_i yields about 31 kJ/mol (kilojoules per mole). Assuming that complete glucose oxidation produces 38 ATP, the total energy stored through ATP production would be 1178 kJ/mol:

$$31 \text{ kJ/mol} \times 38 \text{ ATP} = 1178 \text{ kJ/mol}$$

By contrast, glucose contains exactly 2870 kJ/mol of energy. On this basis, the efficiency of aerobic respiration can be calculated as follows:

$$\frac{(1178 \text{ kJ/mol})}{(2870 \text{ kJ/mol})} \times 100 = 41.0\ \%$$

Therefore, a theoretical maximum of about 41 % of the energy in glucose is converted into ATP. The rest of the potential energy from glucose is dissipated as thermal energy.

An efficiency of 41 % may not seem very high, but it is considerably better than the efficiency of most devices that are designed by human engineers. For example, an automobile is able to convert only about 25 % of the energy from the fuel it burns into the energy of motion. Today, scientists in various fields strive to make the products we use more energy efficient. LED (light-emitting diode) bulbs, for example, produce light using one-third to one-thirtieth of the amount of electricity that incandescent bulbs use. Recall from Chapter 3 that, because of entropy effects, energy transformations are never 100 % efficient. Some energy is always dissipated as thermal energy.

Creatine Phosphate

Having and maintaining a constant supply of ATP is critical for all cells. This is difficult in certain types of cells, such as muscle and brain cells, whose energy demands fluctuate dramatically. These cells may need a sudden burst of ATP energy during periods of high activity, but their ATP demands may be quite low at other times. Some organisms respond to these swings in ATP demand with the use of creatine phosphate. When excess ATP is available in their cells, some organisms use the extra ATP to phosphorylate creatine. When phosphorylated, creatine becomes a high-energy molecule called creatine phosphate:

creatine + ATP → creatine phosphate + ADP

Creatine phosphate can be stored within the cell. The value of creatine phosphate is evident when the ATP demand jumps within the cell. The cell is able to reverse the reaction above to generate additional ATP rapidly:

creatine phosphate → creatine + ATP

This process supplements the amount of ATP that is being produced by aerobic cellular respiration and enables the cell to obtain more ATP than would otherwise by available. Once the cell reserves of creatine phosphate are depleted, they must be regenerated by ATP. This can be done later, when cell demands are lower and surplus ATP can be produced.

Metabolic Rates

An organism's **metabolic rate** is the amount of energy it expends over a specified time. The metabolic rate is equivalent to the overall rate of aerobic and anaerobic respiration reactions. Energy usage increases and decreases depending on the amount of work done by an organism, spanning from intense physical exertion to a state of rest. Humans at rest use energy to breathe and maintain body temperature, to digest food and produce wastes, and even to think. The baseline amount of energy that is used during a state of rest is defined as the **basal metabolic rate (BMR)**, measured in kilojoules per square metre of surface area per hour (kJ/m^2/h). The BMR energy consumption is about 60 to 70 % of the total daily energy used by a human body. BMR varies between individuals and throughout our lifetime, depending on gender, growth and development, age, muscle mass, and health. For example, BMR is greatly reduced with an increased percentage of body fat. In fact, the resting metabolic rate of skeletal muscle is at least three times that of adipose (fat) tissue. Therefore, a higher percentage of body fat reduces the metabolic rate. Research is revealing the many health benefits of maintaining adequate muscle mass and an appropriate percentage of body fat throughout life.

metabolic rate the amount of energy that is expended per unit time in an organism

basal metabolic rate (BMR) the metabolic rate of an organism at rest

Regulating Cellular Respiration

Aerobic cellular respiration requires many enzymes and transport systems. The overall rate of aerobic cellular respiration, which is often measured as the rate of oxygen consumption, is regulated so that ATP synthesis meets the requirements of the cell for chemical energy. In general terms, this is referred to as the concept of supply and demand. The cell does not waste valuable resources by making more of a substance than it needs. Most metabolic pathways are regulated by supply and demand through the process of feedback inhibition: the end products of the pathway inhibit an enzyme early in the pathway (see Section 1.7). The rate of aerobic cellular respiration is controlled by key metabolic intermediates (**Figure 2**).

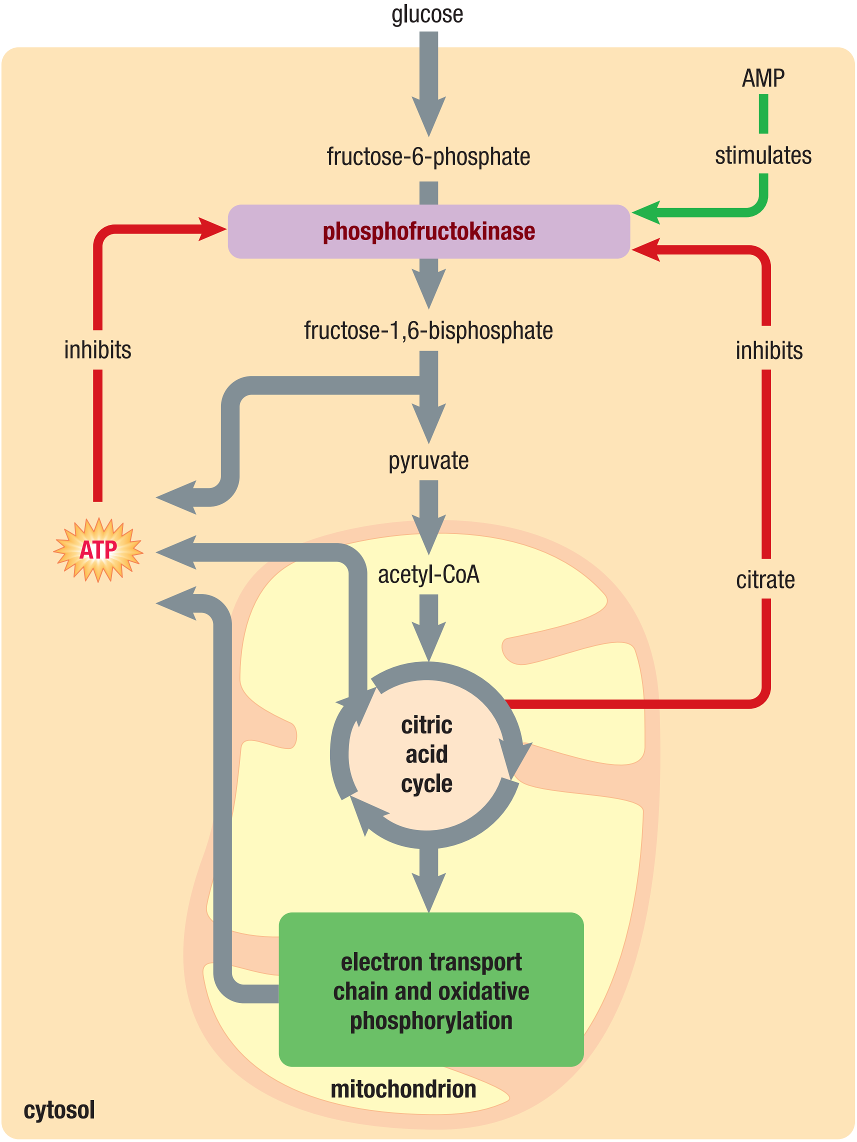


Figure 2 A major mechanism for controlling aerobic cellular respiration is allosteric control of enzymatic activity. Phosphofructokinase is used early in glycolysis. High levels of ATP and the citric acid cycle intermediate citrate inhibit phosphofructokinase. Alternatively, when ATP concentrations are low, the levels of adenosine diphosphate (ADP) and adenosine monophosphate (AMP) increase. AMP is an allosteric activator of the enzyme.

The rate of sugar oxidation by glycolysis is closely regulated by several mechanisms to match the cell's need for ATP. Excess ATP in the cytosol binds to the enzyme phosphofructokinase, acting as a negative regulator, and inhibits its action in glycolysis. The resulting decrease in the concentration of fructose-1,6-bisphosphate slows or stops glycolysis and, as a consequence, the remainder of aerobic cellular respiration. Therefore, glycolysis does not oxidize glucose needlessly when there is an adequate supply of ATP.

The rates of glycolysis and ATP production increase proportionately as cellular activities convert ATP to ADP. This leads to the question of what happens to excess sugars, such as glucose, when they are not needed for metabolism. Usually, they are converted into and stored as fat molecules or as glycogen in the muscle. Like glycolysis, the citric acid cycle contributes to the regulation of glucose oxidation. Some enzymes in the citric acid cycle are also allosterically inhibited by elevated ATP concentrations.

Like ATP, NADH and citrate (an intermediate product of the cycle) also allosterically inhibit phosphofructokinase. The accumulation of NADH and citrate are indicators that downstream reactions are not proceeding as rapidly as they normally would, perhaps because oxygen is limited and oxidative phosphorylation is restricted.

Alternatives to Glucose

The reactions leading from glycolysis through pyruvate oxidation oxidize a range of carbohydrates. In addition to glucose and other 6-carbon sugars, fats and proteins can enter the cellular respiratory pathway at various points (**Figure 3**). The energy content of different types of food is provided in **Table 1**.

Table 1 Energy Content of Different Foods

Type of food	Energy density (kJ/g)
carbohydrates	17
fats	37
proteins	17

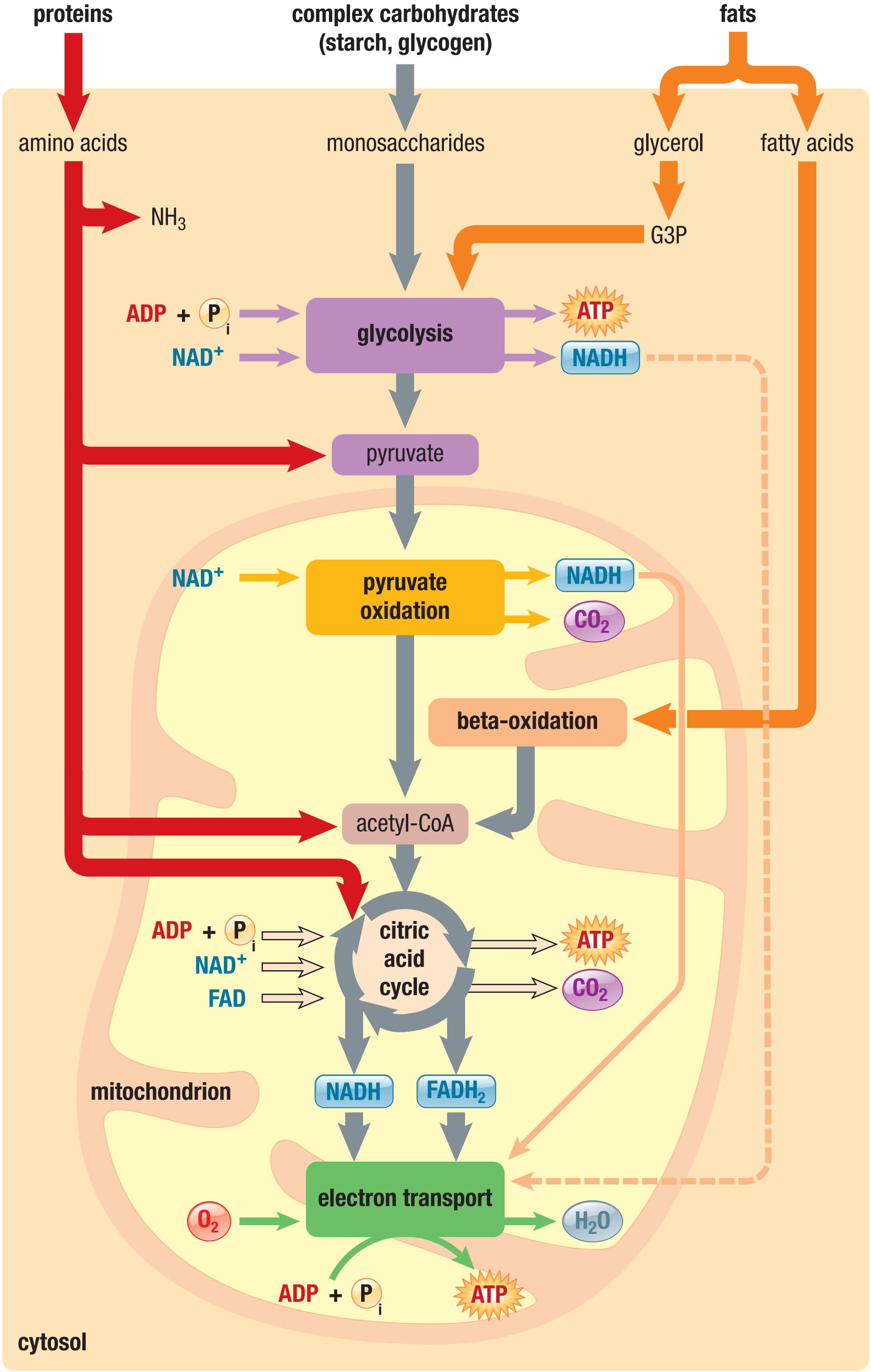


Figure 3 This diagram shows the major pathways that oxidize carbohydrates, fats, and proteins. CoA funnels the products of many oxidative pathways into the citric acid cycle.

Disaccharide carbohydrates, such as sucrose, lactose, and maltose, are easily hydrolyzed into monosaccharides, such as glucose, fructose, and galactose, which enter glycolysis at the early stages. Starch is hydrolyzed into individual glucose monomers using amylase and subsequent enzymes in the digestive tract. Glycogen, a more complex carbohydrate, is hydrolyzed by enzymes in the liver into glucose-6-phosphate (an early substrate molecule in glycolysis).

Among the fats, the triglycerides are major sources of energy for ATP synthesis. Before entering the oxidative reactions, they are hydrolyzed into glycerol and individual fatty acids. The glycerol is converted into glyceraldehyde-3-phosphate before entering glycolysis. The fatty acids (and many other types of lipids) are split into 2-carbon fragments, which enter the citric acid cycle as acetyl groups attached to CoA through a process called fatty acid oxidation, or **beta-oxidation**. Beta-oxidation is the catabolism of fatty acids in the sequential removal of acetyl groups.

beta-oxidation a process in which fatty acids are broken down into acetyl-CoA through catabolism

Proteins are hydrolyzed to amino acids before oxidation. The amino group ($-NH_2$) is removed, and the remainder of the molecule enters the cellular respiration pathway as either pyruvate, acetyl units carried by coenzyme A, or intermediates of the citric acid cycle, depending on the R-group or carbon backbone that is left (Figure 3). For example, the amino acid alanine is converted into pyruvate; leucine is converted into acetyl units; and phenylalanine is converted into fumarate, which enters the citric acid cycle.

The Mass Associated with Food

All carbohydrates are extremely hydrophilic and have a significant amount of water bound to them through hydrogen bonding. The water surrounding carbohydrates is effectively taken out of solution. When you eat a gram of “dry” sugar, you must also consume more than a gram of water to make up for the water that binds to the sugar. For this reason, carbohydrates are heavier than lipids to carry around as a fuel. For animals, especially birds, this is energetically a disadvantage. Fats, however, are hydrophobic. When you consume them, you gain only the mass of the fat. Therefore, a gram of fat really is a gram of fuel. As a result, although many animals consume large quantities of carbohydrates in their diet, the excess carbohydrates are converted into fats for storage. Plants, by comparison, usually store excess energy as carbohydrates (**Figure 4**).

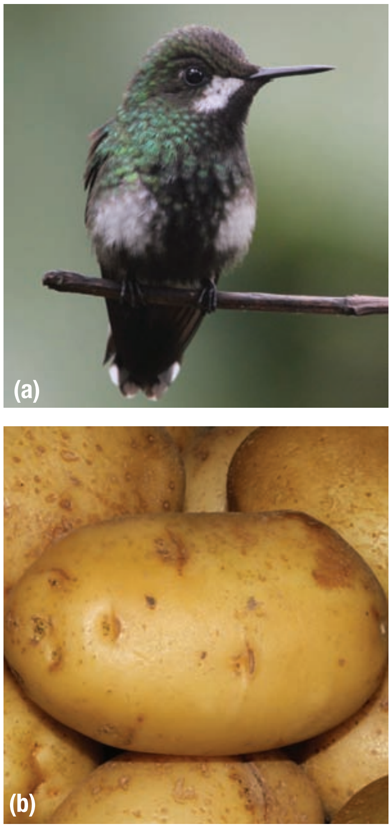


Figure 4 (a) Many animals store excess energy in the form of body fat. This means that hummingbirds, like this green thorntail, do not need to carry the excess water that is bound to very polar carbohydrate molecules. (b) In contrast, most plants store excess energy in the form of carbohydrates. The starch in these potato tubers is bound to large numbers of water molecules.

A Source of Building Blocks

The organic molecules of food are oxidized by cellular respiration to provide the chemical energy that is required to make ATP. These organic molecules also supply cells with the carbon required to synthesize a range of essential molecules that food does not directly provide. The intermediates of glycolysis and the citric acid cycle are routinely diverted and used to assemble the compounds that are needed by the cell. They may be used, for example, as the building blocks for the synthesis of amino acids, or as the pyrimidine and purine bases for the synthesis of nucleic acids. Therefore, a huge degree of metabolic flexibility is required, as illustrated by the fact that many of the reactions shown in Figure 3 are reversible. For example, fatty acids can be used as a source of energy by being oxidized to acetyl-CoA, and excess acetyl-CoA can be removed from the respiration pathway and used to synthesize the fatty acids needed for a range of cellular processes.

4.3 Review

Summary

- Aerobic cellular respiration produces a maximum of 38 ATP per glucose molecule and has a maximum efficiency of about 41 %.
- Creatine phosphate can act as a quick but short-term source of energy in cells.
- Cellular respiration is regulated by negative feedback mechanisms and is able to remain flexible and responsive to changing cellular demands for ATP.
- Metabolic rate and basal metabolic rate vary, based on changes in growth, development, age, health, and gender.
- The overall rate of aerobic cellular respiration is often measured by the rate of oxygen consumption.
- Reactions leading from glycolysis through pyruvate oxidation are used to oxidize the glucose, other carbohydrates, lipids, and proteins that enter the cellular respiratory pathway.
- Due to the significant mass of water bonded to them, carbohydrates are heavier than lipids to carry around as fuel.
- Many important molecules are synthesized from the intermediate chemicals produced during glycolysis and the citric acid cycle.

Questions

1. How many molecules of ATP can NADH and $FADH_2$ yield? Are these numbers exact? Why or why not? K/U
2. (a) How many ATP molecules can be produced from the complete oxidation of one glucose molecule during each phase of aerobic cellular respiration?
   (b) Which ATP molecules are produced using substrate-level phosphorylation versus oxidative phosphorylation? K/U
3. (a) Explain why the actual ATP yield may be less than the maximum possible ATP yield.
   (b) Why is the energy efficiency of ATP production from glucose less than 100 % of the potential energy of glucose? K/U
4. What do you think happens to the thermal energy given off by metabolic processes, such as cellular respiration? Might this thermal energy be useful? A
5. (a) Do online research to determine where creatine phosphate is produced within the human body and how it is used by cells.
   (b) Research the use of dietary creatine supplements. What are the benefits and risks of consuming creatine? 🌐 T/I
6. Explain the difference between metabolic rate and basal metabolic rate, using wording that a non-scientist could understand. K/U C
7. If a person's diet contained only sugar and protein (no fat), could this person still increase his or her percentage of body fat? Why or why not? K/U T/I
8. (a) What prevents us from over-producing ATP?
   (b) Knowing that ATP is a highly unstable molecule, why might it be important not to overproduce it? K/U T/I
9. Why do carbohydrates bind to a significant mass of water while lipids do not? What is the implication of this for an organism's body weight? K/U T/I
10. Plant roots and stems often store large quantities of complex carbohydrates but are low in lipid content. In contrast, plant seeds often contain large amounts of lipid. How might this adaptation be of benefit to plants? T/I
11. What percentage of the food we eat do you think should be in the form of fats, carbohydrates, and proteins? Research the suggested percentages, and make one interpretation based on your findings. How might these numbers be different for a runner versus a weightlifter? 🌐 T/I

🌐 WEB LINK

4.4 Anaerobic Pathways: Life without Oxygen

Although humans have an almost constant requirement for oxygen, other organisms can survive in the absence of oxygen. There are a variety of oxygen-poor environments that do not support aerobic processes. For example, anaerobic environments occur within the human gut, in wet environments (such as swamps and waterlogged soils), deep underground, deep in the oceans, and in landfills. Even though oxygen is not available for aerobic respiration in these environments, energy-rich foods are available for any organisms that are able to use them. Biological productivity in these environments, however, is inherently low because the energy yields of anaerobic pathways are much lower than the energy yield of aerobic respiration.

There are two anaerobic processes by which certain cells and organisms can oxidize fuel molecules and generate ATP: fermentation and anaerobic respiration. Anaerobic cellular respiration uses an electron transport chain that employs an inorganic substance other than oxygen as the terminal electron acceptor. In contrast, fermentation uses an organic molecule as a final electron acceptor but does not use an electron transport chain. Thus, fermentation is not considered to be a form of respiration.

Fermentation

Imagine a cell is in an environment where the oxygen supply is either very low or absent but glucose is abundant. As you have learned, glycolysis is a universal and ancient pathway that can generate ATP. Therefore, even in the absence of oxygen, cells can take in glucose and use glycolysis for ATP production. However, in addition to glucose, glycolysis requires other reactants—most notably NAD^+, which must be present to remove hydrogen in the glycolysis pathway. Cells have a very limited supply of NAD^+. Therefore, after NAD^+ is reduced to NADH, cells must have a way of removing the hydrogen to regenerate NAD^+. A variety of organisms, including yeast and some bacteria, use fermentation reactions to oxidize NADH to NAD^+ instead of an electron transport chain (**Figure 1**). By performing fermentation, cells can regenerate NAD^+ and allow glycolysis to continue.

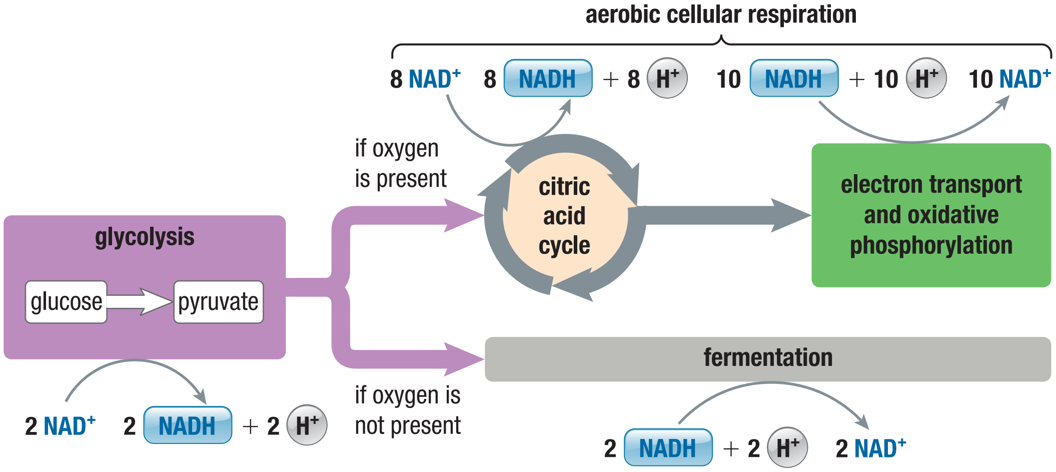


Figure 1 Energy-yielding processes differ in how NAD^+ is regenerated. In cellular respiration, an electron transport chain oxidizes NADH while fermentation reactions provide an alternative pathway for NADH oxidation.

There are several forms of fermentation that bacteria use to obtain energy, but there are two forms that eukaryotes also use: alcohol (ethanol) fermentation and lactate (lactic acid) fermentation. In some organisms, these pathways are the primary source of energy. In other organisms, these pathways are only used as optional or supplemental sources of energy when oxygen is not available in adequate supply.

Alcohol Fermentation

Alcohol fermentation (or ethanol fermentation) occurs in a variety of organisms, including certain bacteria and yeasts. In alcohol fermentation, the pyruvate that is produced by glycolysis is decarboxylated to form acetaldehyde, which is then used to oxidize NADH (**Figure 2**). The products of these final steps include a molecule of CO_2, a molecule of ethanol, and an NAD^+.

alcohol fermentation a process in which pyruvate is decarboxylated, producing a molecule each of CO_2 and of ethanol, and an NAD^+

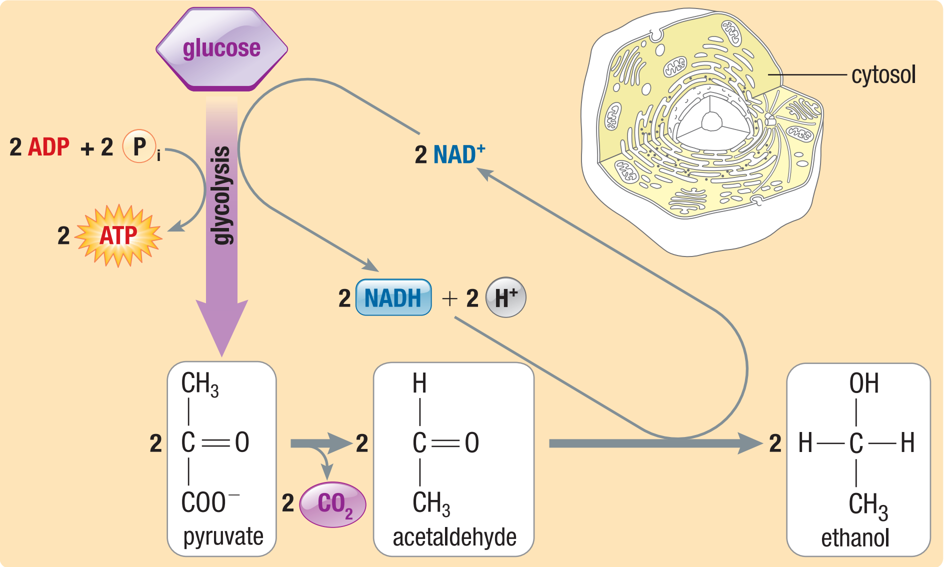


Figure 2 Fermentation reactions produce ethanol.

The following equation summarizes the final steps in alcohol fermentation:

$$\text{pyruvate} + \text{NADH} + \text{H}^+ \rightarrow \text{NAD}^+ + \text{CO}_2 + \text{ethanol}$$

When including glycolysis, which yields the two pyruvate molecules that are used in the reaction above, the overall fermentation pathway results in the formation of two ATPs and the release of carbon dioxide and ethanol waste products, as shown in the following overall equation:

$$\text{glucose} + 2\ \text{ADP} + 2\ \text{P}_i \rightarrow 2\ \text{ATP} + 2\ \text{CO}_2 + 2\ \text{ethanol}$$

Alcohol fermentation by yeasts has widespread commercial applications. Bakers use the yeast *Saccharomyces cerevisiae* to make bread dough rise. They mix the yeast with a small amount of sugar and blend the mixture into the dough, which has a low oxygen level. As the yeast cells convert the sugar into ethanol and CO_2, the gaseous CO_2 expands and creates gas bubbles that cause the dough to rise. In the oven, thermal energy evaporates the alcohol and causes further expansion of the bubbles, producing a light-textured product.

Alcohol fermentation is also used for brewing beer and wine. Winemakers rely on a mixture of wild yeasts and cultivated yeasts to produce wine (**Figure 3**). Alcohol fermentation is an important process in many industries, with over $6 billion in beer and wine produced annually in Canada. The commercial value of yeast has led to yeast being one of the best understood and most studied of all eukaryotic organisms. It was the very first eukaryote to have its entire genome sequenced. CAREER LINK

Alcohol fermentation also occurs naturally in the environment. For example, overripe or rotting fruit often starts to ferment, and birds that eat the fruit may actually become too intoxicated to fly.

Figure 3 Alcohol fermentation occurs in nature. In this photograph, wild yeast cells are visible as a dustlike coating on grapes.

FERMENTATION EFFICIENCIES

Fermentation produces only 2 ATP, compared with up to 38 ATP produced in aerobic respiration. The reason for so much less ATP is that ethanol is produced as a waste product during fermentation, and it is a very energy-rich compound. This is clearly demonstrated by the use of ethanol as a fuel for cooking and some race cars.

Even though fermentation produces much less ATP than aerobic respiration, it is still important in many environments. For example, a dead fish at the bottom of a deep lake is potential food for an anaerobic organism. In an oxygen-rich environment, however, even though an organism could survive using fermentation, it will be rapidly outcompeted by any aerobic organism that is able to extract 19 times as much energy from the same amount of food.

Lactate Fermentation

lactate fermentation a process in which pyruvate reacts with NADH and is converted directly into lactate and regenerates NAD^+

Lactate fermentation is used as a primary energy pathway in some bacteria, but it can also be used as a supplemental system in many eukaryotes. Just because a cell uses aerobic cellular respiration does not mean that it cannot also perform fermentation reactions. In humans, lactate fermentation occurs in our muscle cells when strenuous activity causes a demand for ATP that exceeds the rate at which O_2 can be supplied to the electron transport chain for oxidative phosphorylation. When we are breathing deeply and our heart is pumping rapidly, our circulatory system can still only provide a limited amount of oxygen gas each second. As a result, there is an upper limit on the rate at which oxygen can be supplied to cells and the rate at which aerobic pathways can generate ATP. Even as mitochondria are working rapidly to generate ATP, they are ultimately limited by the amount of available O_2. To maximize ATP production, glycolysis proceeds rapidly, yielding 2 ATPs for every glucose, and any excess pyruvate that is formed in the cytosol is converted into lactate. This pathway regenerates NAD^+, which can be used to maintain a high rate of glycolysis and increases ATP production. If high energy demands continue, significant quantities of lactate can accumulate in cells (**Figure 4**). Following strenuous exercise, when the oxygen content of the muscle cells returns to normal levels and ATP demands have fallen, the reaction is reversed. The reverse reaction regenerates pyruvate and NADH, which can be oxidized by the citric acid cycle and electron transport chain. At one time, the accumulation of lactate (in the form of lactic acids) in muscle tissue during strenuous exercise was thought to be the primary cause of muscle stiffness and soreness. This is now known not to be the case. Lactate levels in muscles generally return to normal within an hour after intense exercise.

Figure 4 Clara Hughes is a Canadian speed skater. In this photograph, she is competing in a 5000 m race. Lactate accumulates in muscle cells during such long and energy-demanding events.

During lactate fermentation, pyruvate oxidizes NADH and is converted directly into lactate and regenerates NAD^+ (**Figure 5**). This reaction commonly occurs in the cytosol.

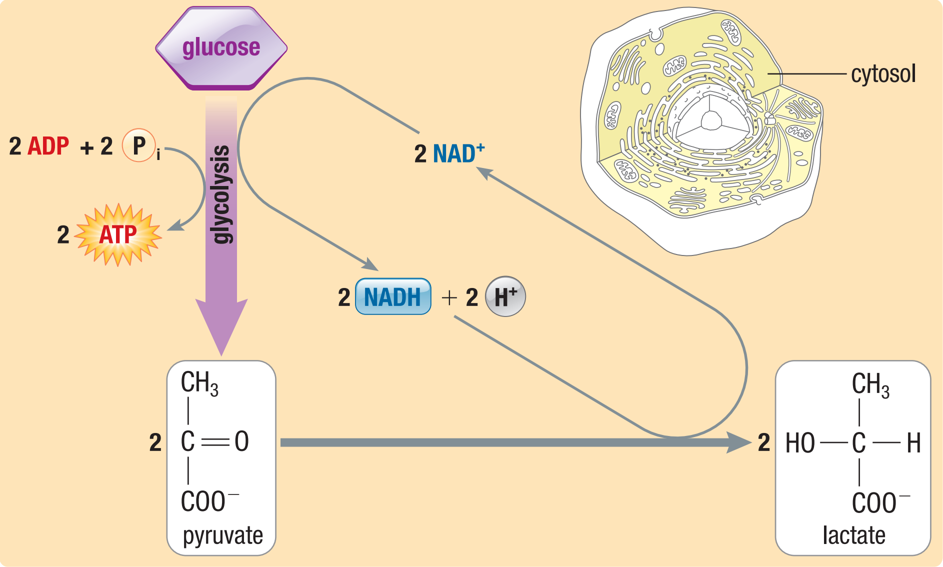


Figure 5 Fermentation reactions that produce lactate

The following equation summarizes the final steps in lactate fermentation, beginning with a single pyruvate:

$$\text{pyruvate} + \text{NADH} + \text{H}^+ \rightarrow \text{NAD}^+ + \text{lactate}$$

The efficiency of lactate fermentation is the same as the efficiency of alcohol fermentation, resulting in 2 ATPs formed per glucose and a similar overall equation:

$$\text{glucose} + 2\ \text{ADP} + 2\ \text{P}_\text{i} \rightarrow 2\ \text{lactate} + 2\ \text{ATP}$$

Notice that, in both alcohol and lactate fermentation, the only reactants other than ADP and P_i are food molecules—in this case, glucose.

Certain bacteria also produce lactate as their fermentation product. The sour taste of buttermilk, yogurt, and dill pickles is a sign of their activity. As well, lactic acid fermentation is used for making some cheeses.

LACTATE THRESHOLD AND OXYGEN DEBT

The rate at which oxygen can be supplied to mitochondria is not always sufficient to meet all of the energy demands of the cell. Therefore, lactate production is ongoing throughout the duration of highly strenuous physical activity. The lactate that is produced is transported from the muscles to the liver, where it is oxidized back to pyruvate so that it does not build up in muscle tissue. The point at which lactate production is too high for transport out of muscles to keep up is called the lactate threshold. This value can be increased by individuals through training, and it is useful for setting exercise intensity limits in endurance sports. The process of lactate fermentation results in an oxygen debt. By taking deeper and more frequent breaths, the body brings in large quantities of oxygen to diminish the oxygen debt.

Investigation **4.4.1**

Observing the Products of Fermentation (p. 200)

In this investigation, you will test for the products of fermentation and examine the ability of yeast to use different substances as food sources.

UNIT TASK **BOOKMARK**

You may find the information you learn in the Research This: Putting Microbes to Work useful as you research the Unit Task on page 252.

Research This

Putting Microbes to Work

Skills: Questioning, Researching, Evaluating, Communicating

SKILLS HANDBOOK **A4.1**

Fermentation plays a vital role in the production of many foods and beverages. In this activity, you will investigate a commercial application that uses fermentation to make a product. Examples of products are bread, beer, wine, liquor, sauerkraut, yogurt, cheese, pickles, and Japanese fermented soybeans.

1. Choose a drink or food that is produced by fermentation.
2. Research the drink or food you chose using the Internet and other resources.

A. What is (are) the key organism(s) that drive the fermentation process? What are their scientific names? T/I

B. What physical and chemical conditions are used to create an environment for the fermentation of the product? How does the industry set up the process of fermentation? T/I

C. Name some environmental conditions that can influence the quality or success of the fermentation process. For example, how do water quality parameters, such as pH, temperature, and oxygen, affect fermentation? T/I

D. How does the action or products of fermentation create or enhance the product you chose? T/I

E. Share your results with your classmates through a poster or presentation. Be sure to mention anything especially interesting you found out while doing your research. C

WEB LINK

Anaerobic Respiration

Although they lack mitochondria, many prokaryotes have cellular respiration electron transport chains. These electron transport chains are located on internal membrane systems derived from the plasma membrane. Some are very similar to those found in the mitochondria of eukaryotes and use O_2 as the terminal electron acceptor. Other prokaryotes, however, have electron transport chains that use substances other than O_2 as the terminal electron acceptor and are said to undergo anaerobic respiration. For example, sulfate, SO_4^{2-}; nitrate, NO_3^-; and the iron ion, Fe^{3+}, are common electron acceptors used by many groups of prokaryotes that do not use O_2 as the terminal electron acceptor.

Organisms that can use these electron acceptors instead of oxygen are common in soils deep underground and in the sediments of marshes, wetlands, and lakes (**Figure 6**). Some wetlands have a strong unpleasant smell, similar to rotten eggs. This smell is produced when anaerobic sulfur-reducing bacteria in the bottom sediments release hydrogen sulfide, H_2S. During anaerobic respiration, these cells use SO_4^{2-} as the terminal electron acceptor (instead of O_2), which results in H_2S as the end product of the electron transport chain (instead of H_2O).

Figure 6 Bogs commonly have anaerobic zones that produce hydrogen sulfide, H_2S.

4.4 Review

Summary

- Fermentation pathways enable organisms to use glycolysis as a source of ATP, without an electron transport chain.
- Alcohol fermentation is performed by yeast and has significant commercial value.
- Lactate fermentation in muscles provides a supplementary source of ATP when energy demands are very high.
- Anaerobic respiration uses inorganic substances other than O_2 as terminal electron acceptors in an electron transport chain.

Questions

1. Compare aerobic respiration and fermentation in terms of the amount of ATP that can be generated from a single glucose molecule. K/U
2. (a) What is the difference between fermentation and glycolysis?
   (b) Why do cells rely on fermentation rather than glycolysis alone? K/U
3. Describe one advantage and one disadvantage of a species that is able to perform fermentation. How do the advantage and disadvantage influence the energy efficiency of the species and where the species can live? T/I
4. (a) Explain the anaerobic pathway that is used to create a loaf of bread. How does this pathway work?
   (b) Name two other products that use the same pathway.
   (c) Explain this pathway to someone who routinely bakes but is not a scientist. K/U C
5. Do our muscle cells produce alcohol? Given that alcohol and lactate fermentation both yield two ATP molecules for every glucose molecule, do you think it would make any difference which pathway was used? Explain. K/U A
6. Identify some environments in which anaerobic respiration takes place. K/U
7. Using what you know about lactic acid fermentation, explain why a person could not perform strenuous exercise indefinitely. K/U T/I
8. How could you increase the amount of time that you can exercise comfortably? K/U
9. Imagine that a muscle cell had a limited number of mitochondria but a very high oxygen supply. If this muscle cell were required to generate a great deal of power, do you think it would benefit from lactate fermentation? Why or why not? T/I
10. Some mammals have an exceptional ability to go for extended periods of time without breathing. Research the diving behaviour of sperm whales (**Figure 7**) and elephant seals. How long can these organisms go without surfacing for air? What special adaptations do these animals have to meet the oxygen and ATP demands of their cells? T/I

Figure 7

WEB LINK

Beetroot Juice

SKILLS HANDBOOK A3

ABSTRACT

Recent scientific findings suggest that consuming beetroot juice as a dietary supplement can decrease systolic blood pressure, reduce oxygen demand during moderate exercise, and increase endurance during strenuous exercise. Studies have found that after only three days of dietary beetroot juice supplementation, oxygen demand is significantly decreased and endurance is increased. Beetroot juice contains inorganic nitrate, NO_3, which converts to nitrite, NO_2^-, and nitric oxide, NO, in the body. Scientists have hypothesized that the reduced oxygen demand may be caused by NO increasing the efficiency of oxidative phosphorylation. Scientists believe that either mitochondrial proton leakage through the inner membrane is decreased or slippage of the proton pumps in the electron transport chain is reduced. Another possible reason for the reduction in O_2 demand is that NO_2^- could serve as the terminal electron acceptor instead of O_2. For this process to take place, NO_2^- would have to have a regeneration pathway in the mitochondria. To date, supplementing nitrate in the diet is the only method that researchers have found to decrease the oxygen uptake required by the body when increasing physical endurance. Even training longer and harder does not result in the same outcomes for the body.

Introduction

Recent studies by Bailey et al. (2009), Lansley et al. (2011), and Lundberg et al. (2011) have shown that consuming beetroot juice can have a significant influence on O_2 uptake and metabolic activity in humans. This has implications for athletes, as well as the general public. As further studies are implemented, an understanding of the relationship between beetroot juice and health will expand.

Because research into the health benefits of beetroot juice is relatively new, the current body of knowledge is incomplete. Research conducted by Bailey et al. (2009) at the University of Exeter in the United Kingdom found that beetroot juice increases endurance and reduces systolic blood pressure. Drinking beetroot juice reduces the amount of O_2 that must be consumed while exercising, which improves performance. One study found that people who drank beetroot juice were able to exercise for 16 % longer. Another study found that beetroot juice reduced the effort of moderate exercise by 19 % because of reduced oxygen demand.

Beetroot juice has two main physiological effects. It widens blood vessels, which decreases blood pressure and improves the flow of blood in the body. It also decreases the amount of O_2 needed by muscles to perform work, which increases endurance during exercise (**Figure 1**).

Figure 1

Regulating Mitochondrial Respiration

The nitrate that is provided by the intake of beetroot juice has important implications for the functions of mitochondria and for aerobic cellular respiration. The decrease in O_2 demand during exercise is hypothesized to be due to NO increasing the efficiency of oxidative phosphorylation. The efficiency of oxidative phosphorylation may be improved because of a reduction in the slippage of mitochondrial proton pumps. It is also possible that mitochondrial effectiveness in the production of ATP is linked to uncoupled cellular respiration. Uncoupled respiration is the process that occurs when protons leak across the inner membrane and the energy that is released during electron transport is released as thermal energy instead of being converted to ATP. Reducing proton leakage would thus increase ATP and improve exercise capabilities.

Another possible explanation is that NO_2^- acts as a terminal electron acceptor, instead of O_2, in the production of ATP. This would decrease the O_2 required for an equivalent amount of ATP to be synthesized during respiration. For respiration to proceed, there would need to be an NO_2^- regeneration pathway so that availability would not be limited. Increasing the number of protons used per molecule of O_2 oxidized or using NO_2^- as an alternative electron acceptor would decrease the O_2 demand during mitochondrial ATP synthesis.

Effects on Exercise

The intake of NO_3^- results in increased muscle oxygenation and increased blood volume caused by NO production. In one study, the intake of NO_3^- caused a reduction in the O_2 required to perform moderate exercise by 19 %. As noted above, this may be caused by more protons being used per O_2 consumed or an alternative electron acceptor, such as NO_2^-, being involved. The results were different for moderate versus strenuous exercise, indicating that the effect of NO_2^- and/or NO on the body varies depending on the type of physical activity. The pulmonary uptake of O_2 was reduced during strenuous exercise and the time to exhaustion was increased by 16 % (**Figure 2**).

Figure 2 Nitrate in beetroot juice can increase endurance during strenuous exercise, such as rock climbing.

Future Research

Studies to date have shown that drinking beetroot juice for as little as a few days can decrease systolic blood pressure and reduce O_2 demand in the production of ATP during physical activity. Based on the current state of knowledge, no other method has the same effect as NO_3^- on reducing O_2 demand and increasing endurance. Future studies could investigate the effects of beetroot juice or other NO_3^--containing supplements on the physical health and performance levels of people with cardiovascular, metabolic, or respiratory diseases. Understanding the connection between NO_3^- intake and exercise has the potential to change many lives.

It is important to note, however, that while the consumption of beetroot juice is considered safe, there have been no studies on the long-term benefits and possible side effects of high levels of consumption. For this reason, it is premature to make any conclusive health claims or recommendations.

Further Reading

Bailey, S.J., Winyard, P., Vanhatalo, A., Blackwell, J.R., DiMenna, F.J., Wilkerson, D.P., Tarr, J., Benjamin, N., & Jones, A.M. (2009). Dietary nitrate supplementation reduces the O_2 cost of low-intensity exercise and enhances tolerance to high-intensity exercise in humans. *Journal of Applied Physiology*, 107, 1144–1155.

Lansley, K.E., Winyard, P.G., Fulford, J., Vanhatalo, A., Bailey, S.J., Blackwell, J.R., DiMenna, F.J., Gilchrist, M., Benjamin, N., & Jones, A.M. (2011). Dietary nitrate supplementation reduces the O_2 cost of walking and running: a placebo controlled study. *Journal of Applied Physiology*, 110, 591–600.

Lundberg, J.O., Carlstrom, M., Larsen, F.J., & Weitzberg, E. (2011). Roles of dietary inorganic nitrate in cardiovascular health and disease. *Cardiovascular Research*, 89, 525–532.

WEB LINK

4.5 Questions

1. Research beetroot juice, and write a summary of new findings about the potential health benefits of beetroot juice on oxygen uptake and the metabolic activity in humans. T/I C
2. Why would a decreased demand in O_2 improve physical performance? How might it influence lactate fermentation rates? T/I
3. Based on your understanding of the relationships between oxygen consumption, energy demand, and chemiosmosis, explain how enhancing the pumping of protons within the mitochondria would reduce oxygen consumption and provide more energy. T/I
4. Conduct research to determine a potential mitochondrial regeneration pathway for supplying NO_2^- as an alternative electron acceptor. T/I A
5. Imagine that you are a food scientist who is preparing to investigate the health benefits of beetroot juice. What experiments and research would you conduct? CAREER LINK T/I A

WEB LINK

4.6 Explore an Issue in Metabolism

Diet Programs and Supplements

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Have you ever noticed that there is a huge consumer demand for diets, exercise machines, and supplements to improve self-image, health, and the quality of life (**Figure 1**)? Recently, low-carb diets were on the front covers of books and consumer magazines. Before low-carb diets, there were low-fat diets, the Atkins diet, the South Beach diet, and the Zone. Some diets recommend consuming liquids, high-fibre foods, or "macrobiotics." Other diets recommend consuming large quantities of a single food, such as grapefruit in the grapefruit diet. Are any or all of these diets good for people? Do they help people lose weight and stay healthy, or are they all just commercial gimmicks designed to help sell books, pills, and other products? Dieting is big business!

Figure 1 There are many kinds of diet products available.

It is important to investigate thoroughly the benefits and risks of choices that could have long-term effects on the health of the body. Of all the diets and supplements that are available today, how many are effective? Are they safe? How do supplements and diets affect the functioning of cells in the body? How do changes in cellular functioning caused by diets compare with the changes caused by exercise? These are a few of many questions related to diets. CAREER LINK

In this activity, you will work on your own or in a small group to explore some of the questions about diets. Through investigation, you will become an informed consumer, better able to make wise decisions based on a thorough understanding of cellular respiration and metabolism.

The Issue

You are a consumer health advocate who is writing an article or blog about new diets and supplements that you have seen advertised. You want to inform your readers about whether diets or supplements are safe and effective.

Goal

To evaluate the merits of a specialty diet or dietary supplement for regulating and maintaining a healthy metabolic rate, as an effective and safe method for weight loss, and for overall health

Research

SKILLS HANDBOOK A4.1

Research answers to the following questions and issues related to the diet or supplement you have chosen:

- What are the pros and cons of the specialty diet or supplement? Beware of bias in the sources you use. Some proponents of diets and supplements are selling their products, so consider the value of the information provided by these people. Are they marketing a particular diet or product?
- Are the claims supported by valid and rigorous scientific evidence?
- Determine how the diet or supplement affects the body. Try to determine what physiological effects are taking place. How does the diet or supplement alter the process or pace of cellular respiration in the body?
- If you investigate a specific diet, try to determine the chemical makeup of the foods in the diet. Based on the composition and energy content of the foods, how are they processed during cellular respiration?
- If you investigate a dietary supplement, describe how the substance regulates or influences energy expenditures. WEB LINK

Possible Solutions

You may wish to consider the following factors to help you identify options for your audience:

- What are the risks and benefits of the diet and/or supplement on the body? Does one outweigh the other? Consider the costs and convenience as well as the health implications.
- Based on your findings, do you think some diets and/or supplements would benefit certain people and not others? Why or why not?
- What are the advantages and disadvantages of your selected diet or supplement, compared with increased exercise and/or a general reduction in food consumption?

Decision

Based on your research and analysis, decide whether you would recommend the diet or supplement as a safe and effective health choice. Explain why you made this decision.

Communicate

Present your decision in a written, oral, or visual format. You may choose to create a blog to share your findings, or you may prefer a more formal report. If time permits, your teacher may suggest that you make a short presentation to the class either to promote the diet or supplement, or to speak out against it. Be sure to ask your teacher to approve the format you choose.

Plan for **Action**

Consider the various ways in which people are informed about making wise choices, including the Internet, friends, teachers, books, and television.

Develop a checklist that would be helpful for people to follow when deciding whether to begin a new diet or take a dietary supplement.

WEB LINK

CHAPTER 4 Investigations

Investigation 4.2.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Observing the Products of Cellular Respiration

The Mini Investigation: Observing Evidence of Respiration (Section 4.2) showed that we exhale CO_2 and that it forms a detectable acid in water. The amount of CO_2 that is produced can be quantified using titration. In this investigation, you will use titration to compare the rates of energy consumption at rest, during different activities, and during and after exercise.

Testable Question

During intense exercise, does the body produce more CO_2 per litre of exhaled air, more CO_2 per minute, or both? In other words, do you release more CO_2 in each breath, or do you just breathe deeper and more often?

Hypothesis

Using your results in the Mini Investigation: Observing Evidence of Respiration, form a hypothesis based on the testable question.

Variables

Choose variables to include in your experiment, and ask your teacher to approve them. The dependent variable will likely be the amount of CO_2 produced per litre or per minute. Carefully consider what units you will use, for example, mol CO_2/L or mol CO_2/min.

Equipment and Materials

SKILLS HANDBOOK A1

- lab apron
- safety goggles
- protective gloves
- 2 flasks (250 mL)
- medicine dropper
- stopwatch
- funnel
- standard drinking straw
- large clear plastic bags
- burette
- clamp
- 0.1 mol/L sodium hydroxide, NaOH, solution
- phenolphthalein indicator solution
- distilled water

Do not inhale through the straw. Do not share straws.

Sodium hydroxide solution is corrosive, toxic, and an irritant. It can cause blindness if it is splashed in the eyes. Avoid splashing sodium hydroxide solution on your skin, in your eyes, or on your clothing. Immediately rinse any spills with plenty of cold water, and inform your teacher. Carefully follow your teacher's instructions for disposal.

Phenolphthalein indicator is flammable. Keep it away from open flames.

Procedure

SKILLS HANDBOOK A2.1, A2.2, A5.4

1. Design your own experiment based on the following considerations. Obtain your teacher's approval before proceeding. Put on your lab apron, safety goggles, and protective gloves before you begin your experiment.
   - What type of exercise will you choose to perform, and for how long?
   - How can you measure the rate of CO_2 production in a unit of time? Will you be able to breathe into the solution in the flask while you are exercising?
   - How can you measure the volume of CO_2 per litre of exhaled breath? If you fill a plastic bag while you are resting or exercising, how will you measure its volume and how will you pass the gas through the solution in the flask?
   - Will you conduct more than one trial?

Preparation of Titration and Base Test Solutions

2. A 0.1 mol/L NaOH titration solution will be prepared by your teacher and provided in a labelled flask. Use this solution in Step 4 and in Step 6 with the burette.
3. In another labelled flask, add 150 mL of distilled water and four drops of phenolphthalein indicator solution. Mix by gently shaking the flask. The resulting solution should be clear.
4. Using the medicine dropper, add 0.1 mol/L NaOH, one drop at a time while swirling, until the solution just turns pink and stays pink. This is your base test solution. You will use it to establish a consistent starting point, or set point, for the test solution. When you perform your titration, you will return the solution to the same pink colour.

Performing the Titration

5. Based on your experimental design, pass your exhaled breath through the test solution. The carbon dioxide in your breath will form carbonic acid in the solution causing the pink colour to disappear.
6. Set up your titration (**Figure 1**). Using the burette, slowly add 0.1 mol/L NaOH drop by drop, swirling between each drop, until the test solution just turns pink and stays pink. You are trying to return the solution to the same pH, based on your set point in Step 4. Record the volume of NaOH solution you need to return the solution to the set point. Record all your data in a table.

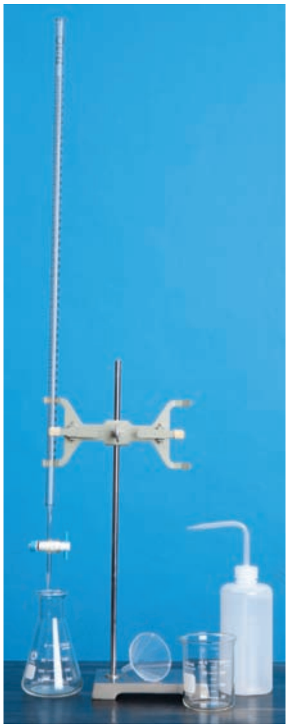


Figure 1 Titration design

7. Remember that CO_2 becomes H_2CO_3 in solution. The mole ratio of the reaction is 2 moles of NaOH for every 1 mole of H_2CO_3. The reaction can be represented as follows:

$$H_2CO_3 + 2\ NaOH \rightarrow 2\ H_2O + Na_2CO_3$$

To calculate the number of moles of exhaled CO_2, determine the number of moles (x) of NaOH used to titrate the solution:

$$\begin{aligned} x &= [\text{NaOH}] \times \text{volume of titrant (in litres)} \\ &= 0.1\ \text{mol/L} \times \text{volume of titrant (in litres)} \end{aligned}$$

Then, divide by 2 because each H_2CO_3 reacted with 2 NaOH.

$$\text{Moles of } CO_2 = \frac{x}{2}$$

8. Repeat Steps 5, 6, and 7 for each experimental trial.

Analyze and Evaluate

(a) Analyze your data graphically. T/I C

(b) During intense exercise, does the body produce more CO_2 per litre of exhaled air, more CO_2 per minute, or both? T/I

(c) Evaluate your hypothesis using the results of the experiment. Was your hypothesis accepted or rejected as a result of your analysis? T/I

(d) Which variable did you choose to test in your experiment? Why did you choose this variable? T/I

(e) What might you change in your design after you evaluated your expected results? T/I

(f) Submit the results of your experiment in journal format, including an abstract. References are not necessary for this investigation. T/I C

(g) Your teacher may ask you to exchange reports with fellow classmates anonymously, for a peer review. C

Apply and Extend

(h) How would this type of experimental design be valuable for coaches and trainers of elite athletes? T/I

(i) Suggest a reason why it is necessary to "scrub" CO_2 from the air aboard a spacecraft or submarine. T/I

(j) Conduct research to determine what a rebreather system is and why it might be used. T/I

WEB LINK

Investigation 4.4.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Observing the Products of Fermentation

Yeast are facultative anaerobes and can perform the anaerobic fermentation of glucose. In this investigation, you will test for the products of fermentation and examine the ability of yeast to use different substances as food sources.

Testable Questions

Part A: Does yeast have the ability to ferment glucose and produce carbon dioxide gas and ethanol?

Part B: Does yeast have the ability to ferment other sugars and artificial sweeteners? Does lactase influence the ability of yeast to use lactose as a food source?

Prediction

Make predictions about the experimental outcome based on the Testable Questions.

Variables

Which are the dependent (responding) variables and which are the independent (manipulated) variables?

Equipment and Materials

- safety goggles
- lab apron
- 4 flasks (100 mL) and 1 stopper
- 6 test tubes (15 mL) with 1-hole rubber stoppers
- wax pencil (for marking test tubes)
- ruler
- 6 large beakers (400 mL)
- thermometer
- stopwatch
- 50 mL glucose suspension (10 %)
- 50 mL yeast suspension (1 package per 100 mL of water)
- cotton batting
- limewater
- warm water (35 °C)
- 10 mL of each of the following solutions: glucose, sucrose, lactose, and artificial sweetener (10 %)
- 10 mL of a suspension of lactose (10 %) with a pinch of lactase (from crushed tablet)
- 10 mL of distilled water

Procedure

SKILLS HANDBOOK A1.2, A2.1, A2.2

Part A: Fermentation of Glucose

1. Put on safety goggles and a lab apron.
2. Label three flasks as "yeast and glucose," "yeast," and "glucose."
3. Add 10 mL of glucose solution and 5 mL of yeast suspension to the "yeast and glucose" flask.
4. As a control, add 10 mL of distilled water with 5 mL of yeast suspension to the "yeast" flask.
5. As a second control, add 5 mL of distilled water with 10 mL of glucose solution to the "glucose" flask.
6. To reduce air turbulence, place cotton batting in the mouth of the flasks. CO_2, if produced, will accumulate in the flasks, because CO_2 is denser than air.
7. After 24 h, remove the cotton batting and carefully smell the contents of each flask. You may be able to detect a slight alcohol odour.
8. Test the gas in each flask for the presence of CO_2. To do this, slowly "pour" the invisible gas mixture into a flask that contains 25 mL of limewater. Be careful to avoid pouring any liquid into the limewater. Stopper the limewater flask, and swirl the contents to mix the limewater with the gas. Look for any evidence of a precipitate, and record your observations. Rinse out the flask. Add 25 mL of fresh limewater before testing the next gas sample.

Part B: Fermentation of Sweeteners

9. Use a ruler to place graduation marks at 0.5 cm intervals along the sides of six test tubes.
10. Prepare six beakers of warm water (35 °C). The beakers should be two-thirds full of warm water.
11. Label the six test tubes as "glucose," "sucrose," "lactose," "artificial sweetener," "lactose and lactase," and "distilled water."
12. Add 10 mL of the appropriate solution to each test tube.
13. Add 5 mL of yeast suspension to each test tube. The test tubes should be full.
14. After the mixtures are placed in the test tubes, seal the test tubes with one-hole stoppers. Make sure that there are no air bubbles in the test tubes.
15. Hold one test tube. Cover the hole in the stopper with your finger, and invert the test tube into a beaker of warm water. Repeat this process for all six solutions, using a different beaker for each solution.
16. Record the amount of gas produced after 1, 5, and 10 min using the graduation marks on the test tubes.

Analyze and Evaluate

(a) In Part A, what happened to the gas in the "yeast and glucose" test tube when you added limewater? T/I

(b) What happened to the solution in the "yeast" and the "glucose" test tubes? Account for your findings. T/I

(c) In Part B, did gas accumulate in the top of the inverted test tubes? Explain these results. T/I

(d) Was there a difference in your results for the six solutions? What structural features of the sugars do you think are responsible for the results you observed? T/I

(e) Can all sugars be used as a food source by yeast? T/I

(f) What are the monosaccharides that make up lactose (a disaccharide)? T/I

(g) Conduct online research to determine if yeast is able to ferment the monomers of sucrose (glucose and fructose) and lactose (glucose and galactose). T/I

Apply and Extend

(h) Do you think milk would be a suitable food source for yeast? Predict and then find out if yeast is used in the production of yogurts and cheeses. T/I A

(i) People who are lactose intolerant often suffer from gas pains. The lactose is consumed by anaerobic bacteria in the gut. Conduct online research to find out what gas or gases are produced in the gut. T/I A

WEB LINK

CHAPTER 4 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 166. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 166. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

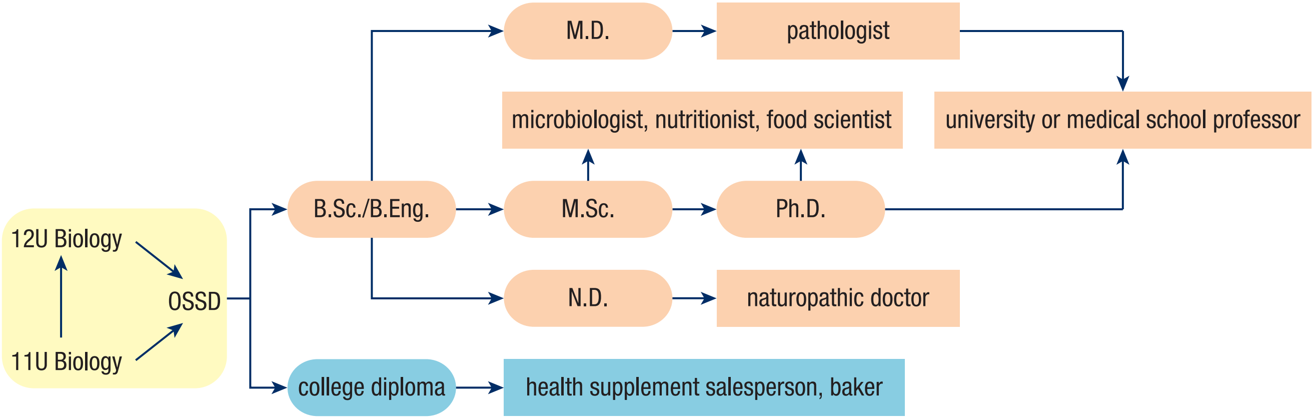
aerobic cellular respiration (p. 168)
obligate aerobe (p. 168)
substrate-level phosphorylation (p. 169)
oxidative phosphorylation (p. 169)
glycolysis (p. 169)
pyruvate oxidation (p. 169)
citric acid cycle (p. 169)
anaerobic respiration (p. 170)
fermentation (p. 170)
obligate anaerobe (p. 170)
facultative anaerobe (p. 170)
decarboxylation reaction (p. 175)
dehydrogenation (p. 175)
proton gradient (p. 180)
proton-motive force (p. 180)
chemiosmosis (p. 180)
metabolic rate (p. 185)
basal metabolic rate (BMR) (p. 185)
beta-oxidation (p. 188)
alcohol fermentation (p. 191)
lactate fermentation (p. 192)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to cellular respiration and fermentation that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, main duties and responsibilities, working conditions, and setting. Also outline how the career benefits society and the environment.


M.D.
pathologist
microbiologist, nutritionist, food scientist
university or medical school professor
12U Biology
OSSD
11U Biology
B.Sc./B.Eng.
M.Sc.
Ph.D.
N.D.
naturopathic doctor
college diploma
health supplement salesperson, baker

CAREER LINK

CHAPTER 4 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. The reactions of photosynthesis trap light energy and use it to convert carbon dioxide and water into another substance. What is this substance? (4.1) K/U
   (a) pyruvate
   (b) ATP
   (c) sugar
   (d) NADH
2. What is the name of the process in which organic compounds are broken down by cells to make ATP? (4.1) K/U
   (a) photosynthesis
   (b) chemosynthesis
   (c) cellular respiration
   (d) cellular autosynthesis
3. Glycolysis begins with glucose. What is one product of this reaction? (4.2) K/U
   (a) PGAL
   (b) pyruvate
   (c) acetyl-CoA
   (d) lactate
4. The products of pyruvate oxidation are CO_2, NADH, H^+, and another substance. What is this substance? (4.2) K/U
   (a) lactate
   (b) citric acid
   (c) oxaloacetic acid
   (d) acetyl-CoA
5. What is the approximate energy efficiency of aerobic cellular respiration? (4.3) K/U
   (a) 6 %
   (b) 20 %
   (c) 40 %
   (d) 100 %
6. Which phrase describes the basal metabolic rate? (4.3) K/U
   (a) the minimum energy used when at rest
   (b) the maximum energy used during strenuous exercise
   (c) the average energy used during moderate exercise
   (d) the estimated energy needed for a specific activity
7. Which important molecule is generated by both lactate fermentation and alcohol fermentation? (4.4) K/U
   (a) ATP
   (b) NADH
   (c) CO_2
   (d) NAD^+
8. In alcohol fermentation, which substance is reduced to produce ethyl alcohol? (4.4) K/U
   (a) NAD^+
   (b) NADH
   (c) lactate
   (d) acetaldehyde
9. According to new research, what is beetroot juice effective for? (4.5) K/U
   (a) increasing mitochondrial efficiency
   (b) reducing blood pressure
   (c) reducing oxygen demand
   (d) all of the above

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Glucose supplies most of the chemical energy that can be immediately used by cells. (4.1) K/U
11. Anaerobic respiration relies on organic compounds other than oxygen to act as the final oxidizing agents in the production of ATP. (4.1) K/U
12. During aerobic cellular respiration, the cell produces a majority of its ATP through substrate-level phosphorylation. (4.1) K/U
13. The reactions of the citric acid cycle occur on the outer membrane of the mitochondria. (4.2) K/U
14. Electrons gain energy as they move along the electron transport chain. (4.2) K/U
15. In the electron transport chain, electrons are pushed through by the electronegativity of O_2. (4.2) K/U
16. Many metabolic pathways are regulated by supply and demand, through the process of feedback inhibition. (4.3) K/U
17. If excess ATP is present in the cytosol, it binds to an enzyme that increases the reactions of glycolysis. (4.3) K/U
18. Carbohydrates are an efficient way to store energy because they do not require water to be stored in order to be metabolized. (4.3) K/U
19. Yeasts produce alcohol and carbon dioxide in the process of lactate fermentation. (4.4) K/U
20. NAD^+, ethanol, and carbon dioxide are produced when pyruvate from glycolysis oxidizes NADH. (4.4) K/U
21. Pyruvate is converted to lactate through the reduction of NADH to NAD^+. (4.4) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 4 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which organic compound is found in most cells? (4.1) K/U
   - (a) oxygen
   - (b) sodium
   - (c) glucose
   - (d) water
2. Which substance is an energy compound that is synthesized by plants and animals? (4.1) K/U
   - (a) adenosine triphosphate (ATP)
   - (b) chlorophyll
   - (c) cellulose
   - (d) ethyl alcohol
3. Which gas is used as a reactant in the process of aerobic cellular respiration in green plants? (4.2) K/U
   - (a) methane
   - (b) nitrogen
   - (c) oxygen
   - (d) carbon dioxide
4. What does *x* represent in the equation for aerobic cellular respiration, shown below? (4.2) K/U

   $$\text{glucose} + \text{oxygen} + \text{ADP} + \text{P}_\text{i} \rightarrow \text{water} + \text{carbon dioxide} + x$$

   - (a) lactate
   - (b) ATP
   - (c) ethyl alcohol
   - (d) ADP
5. What is the role of oxygen in aerobic cellular respiration? (4.2) K/U
   - (a) It acts as a coenzyme.
   - (b) It serves as an amino group.
   - (c) It combines with carbon to form carbon dioxide.
   - (d) It combines with hydrogen atoms to form water.
6. Approximately how many molecules of ATP, per molecule of glucose, are produced in aerobic cellular respiration? (4.3) K/U
   - (a) 2
   - (b) 8
   - (c) 24
   - (d) 38
7. In ADP and ATP, energy is stored in electrons. Where are these electrons located? (4.3) K/U
   - (a) in the adenine group
   - (b) in phosphate bonds
   - (c) in carbon groups
   - (d) in water and oxygen
8. Which process regenerates NAD^+ for glycolysis when oxygen is not present? (4.4) K/U
   - (a) citric acid cycle
   - (b) pyruvate oxidation
   - (c) fermentation
   - (d) substrate-level phosphorylation
9. In some animals, when oxygen supplies are low in the cells, pyruvate can be converted to another substance. What is this substance? (4.4) K/U
   - (a) nucleic acid
   - (b) carbon dioxide
   - (c) glucose
   - (d) lactate
10. Which molecule can be used as a terminal electron acceptor in anaerobic respiration? (4.4) K/U
    - (a) SO_4^{2-}
    - (b) Fe^{3+}
    - (c) NO^{3-}
    - (d) all of the above

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Oxidative phosphorylation forms ATP directly, through a series of redox reactions that involve a final electron acceptor. (4.1) K/U
12. Obligate aerobes can live without oxygen. (4.1) K/U
13. Glycolysis requires two ATP molecules during the investment phase. (4.2) K/U
14. The final hydrogen acceptor in aerobic cellular respiration is water. (4.2) K/U
15. The process of alcohol fermentation is more efficient than aerobic cellular respiration for extracting energy from food. (4.3) K/U
16. During strenuous exercise, lactate fermentation is the result of an oxygen debt in the muscles. (4.4) K/U
17. Fermentation occurs in the absence of oxygen. (4.4) K/U
18. In lactate fermentation, NADH transfers its electrons to glucose. (4.4) K/U

Match each term on the left with the most appropriate description on the right.

19. (a) glycolysis
    (b) cytosol
    (c) fermentation
    (d) NAD^+
    (e) aerobic respiration

    (i) electron acceptor
    (ii) first pathway of cellular respiration
    (iii) location of glycolysis
    (iv) cellular respiration that uses oxygen
    (v) glycolysis and anaerobic pathways

    (4.1, 4.2, 4.3) K/U

Write a short answer to each question.

20. Differentiate between the two types of cellular respiration. (4.1) K/U
21. What is the matrix of a mitochondrion? (4.1) K/U
22. Create a table to summarize the main categories of organisms, based on oxygen requirements. (4.1) K/U C
23. Imagine that a younger student has asked you about your homework and you are trying to explain chemiosmosis in simple terms. Use an analogy to help you explain the role of chemiosmosis in aerobic cellular respiration. (4.2) K/U C
24. What are the waste products of aerobic cellular respiration in humans, and how are they handled? (4.2) K/U
25. What products of the citric acid cycle are used by the electron transport chain? (4.2) T/I
26. Which anaerobic ATP-producing process can occur in nearly all animals? (4.4) K/U

Understanding

27. Explain how the folding of the inner mitochondrial membrane benefits aerobic respiration. (4.1) K/U
28. Glycolysis begins with glucose, yet many animals can survive on diets that are extremely low in carbohydrates. Account for this observation. (4.1) K/U T/I
29. Compare the locations of each process in prokaryotes and eukaryotes. (4.1) K/U
    (a) aerobic cellular respiration
    (b) glycolysis
    (c) citric acid cycle
    (d) electron transport
30. Design a flow chart that summarizes the four stages of aerobic cellular respiration. Include the major reactants and products. (4.1) K/U C
31. Use a diagram to explain the source of most of the energy in the biosphere. Your diagram should show where the energy comes from and what processes it undergoes before it can be used in living cells. (4.1) K/U C
32. Bacteria are often used to clean up groundwater pollutants, such as hydrocarbons. Use your knowledge of cellular respiration to explain why bacteria are useful as a remediation alternative. (4.1) K/U A
33. Describe the structure and function of an ATP molecule, and explain why it is so valuable to a cell. Include diagrams or sketches. (4.1) K/U C
34. Create a table to identify the major electron carriers of aerobic cellular respiration, and briefly explain how they are altered to transfer energy in a cell. Include diagrams in your table. (4.2) K/U C
35. Create a graphic timeline to summarize the events that occur from the end of glycolysis through to the first reaction of the citric acid cycle. (4.2) K/U C
36. Use a balanced redox equation and a brief description to explain the fate of the electrons at the end of the electron transport chain. (4.2) K/U C
37. List three reasons why glycolysis is considered to be the most fundamental and probably most ancient metabolic pathway. (4.2) K/U
38. Explain what would happen to energy production in the mitochondria if ATP synthase stopped functioning. (4.2) K/U
39. Summarize the citric acid cycle. Include both the reactants and products that result from each molecule of glucose that enters the cycle. Also include diagrams. (4.2) K/U C
40. (a) What carriers supply the electrons that pass through the electron transport chain?
    (b) In what stage or stages of respiration are the electrons produced? (4.2) K/U
41. Approximately how much ATP is produced through the entire process of aerobic cellular respiration? Create a balance sheet for the stages (glycolysis, citric acid cycle, chemiosmosis), and give the total amount of ATP. (4.3) K/U T/I C
42. Explain how the citric acid cycle is regulated to meet the energy needs of a cell, while not needlessly consuming cellular energy. (4.3) K/U
43. Use diagrams and a potential energy chart to show the change in energy that occurs when ATP is converted to ADP + P_i. (4.3) K/U C

44. Is the BMR the same for both of the individuals shown in **Figure 1**? Explain your reasoning. (4.3) K/U T/I

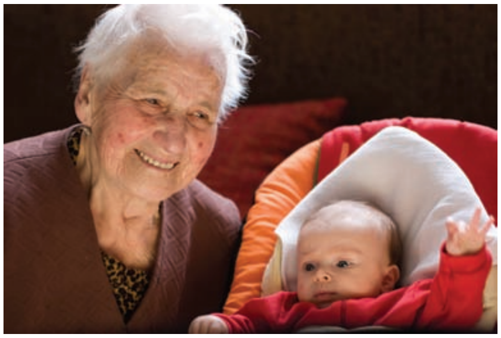


Figure 1

45. Glycolysis produces only a small percentage of the energy that would be produced if the same quantity of glucose was completely oxidized. What happens to the rest of the energy in the glucose? (4.3) K/U T/I

46. Explain what would cause cells in your body to undergo lactic acid fermentation. (4.4) K/U

47. As athletes perform physical activity, they exert energy (in watts). An athlete's blood pH was measured during a workout, and the results were plotted in a graph (**Figure 2**). Explain the results, as shown in the graph. (4.4) T/I C

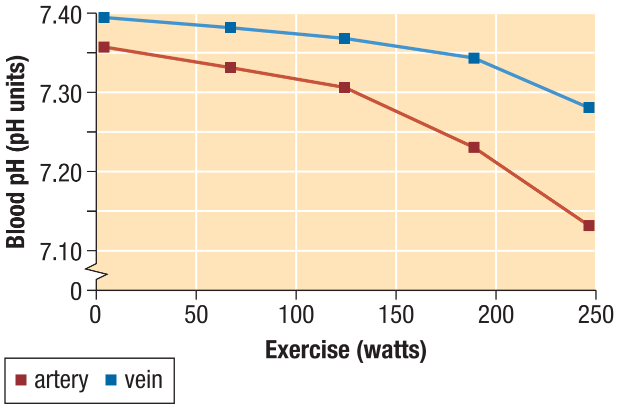


Figure 2

48. Describe how alcohol fermentation is used in the production of industrial ethanol. (4.4) K/U T/I A

49. Fermentation of sugars results in the production of ethanol that becomes toxic to the yeast at approximately 7 % to 10 %. In humans, no such toxicity exists during anaerobic respiration. Explain why the toxicity that occurs in yeast does not occur in humans. (4.4) K/U A

50. List three environments where anaerobic respiration or fermentation takes place. Explain. (4.4) K/U A

51. Compare lactic acid fermentation with alcohol fermentation. Discuss where they occur and the products that are formed in each process. (4.4) K/U

52. Suppose that you prepared a suspension of yeast in a warm sugar solution, and you added sugar every hour for 12 h. You collected and analyzed the gas that was produced by the yeast suspension. Then you plotted your results in a graph (**Figure 3**). Explain your results. (4.4) K/U T/I

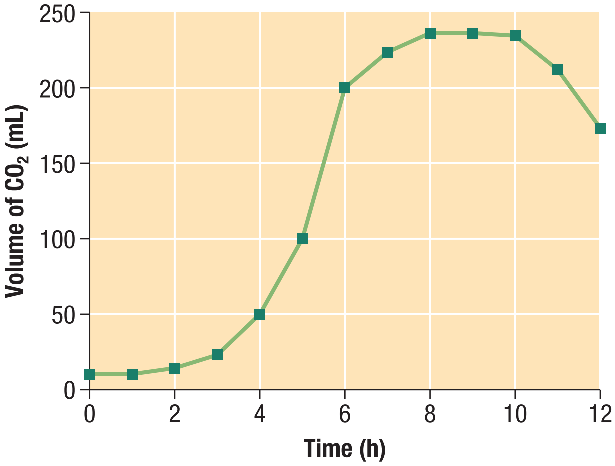


Figure 3

53. (a) Which compounds react during lactate fermentation?
    (b) Which of these compounds pass high-energy electrons to the other? (4.4) K/U

Analysis and Application

54. (a) Draw a diagram of a cell that contains one mitochondrion.
    (b) Use labels to indicate where glycolysis, pyruvate oxidation, the citric acid cycle, the electron transport chain, and oxidative phosphorylation occur.
    (c) Indicate the regions of low and high H^+ concentration. (4.1) K/U T/I C

55. Imagine that you are a consulting engineer and your team is in charge of designing an energy system that mimics a mitochondrion. Develop a list of components that would have to be included in your system, and explain why. Include sketches, where necessary, to illustrate your ideas. (4.1) K/U T/I C A

56. Briefly compare and contrast the method of energy transfer from reactants to products in the citric acid cycle with the method of energy transfer when ADP is converted to ATP. (4.2) K/U T/I A

57. Why is the energy that is released from the fermentation of one glucose molecule less than the energy that is released from the aerobic cellular respiration of one glucose molecule? (4.3) K/U T/I

58. If you were a dietician and a client wanted to increase his or her BMR, what major change would you suggest? (4.3) K/U T/I

59. Many eukaryotic organisms do not produce the maximum of 38 ATP molecules for every glucose molecule that is oxidized through aerobic respiration. Explain why. (4.3) K/U T/I

60. If aerobic cellular respiration yields up to 19 times as much energy as anaerobic pathways, what is the advantage of being an anaerobe? (4.4) K/U T/I

61. For animals, what might be an adaptive advantage of using lactate fermentation rather than ethanol fermentation? (4.4) K/U T/I A

62. Vitamin B deficiency is linked to fatigue. (4.3) K/U T/I
    (a) Explain why vitamin B is vital for energy metabolism.
    (b) What are the effects of vitamin B deficiency on aerobic and anaerobic cellular respiration?

63. A high concentration of ATP inhibits the enzymes that are responsible for glycolysis. Construct a flow chart to show how the inhibition of these enzymes is influenced by the level of energy demand within the cell. (4.3) T/I

64. You may have found yourself breathing heavily after strenuous exercise. Knowing what you now know about cellular respiration, explain why you must breathe deeply and heavily even after you stop exercising. (4.4) K/U T/I A

65. Oxidation was historically defined as the combination of a substance with oxygen. Based on what you know about cellular respiration, is this an accurate definition? Explain. (4.4) K/U T/I

66. Suppose that you are growing animal cells in a culture. The cells have been growing well until recently. You analyze the culture and find excess lactate. (4.4) K/U T/I
    (a) What is the most likely reason for the excess lactate?
    (b) Suggest a way to reverse this situation.

67. Erythropoietin (EPO) was developed to treat people with certain types of anemia. It helps to increase red blood cell production. (4.4) K/U T/I
    (a) Describe how and why EPO might help people with anemia.
    (b) Why do you think this drug is banned by the World Anti-Doping Agency for use in endurance sports?

68. The following equations represent key processes in cellular energy pathways. Copy and complete these equations in your notebook. Name the process that is represented by each equation, and describe the organisms and the conditions in which the process occurs. (4.2, 4.4) K/U T/I
    (a) pyruvate + ______ + $H^+ \rightarrow$ ethanol + ______ + ______
    (b) ______ + ______ + $H^+ \rightarrow$ lactate + ______
    (c) pyruvate + ______ + ______ $\rightarrow$
    acetyl-CoA + ______ + ______ + ______

69. A student excels at endurance when doing push-ups. She completes four 2 min trials, resting for 1 min between trials. She records the number of push-ups that she does in each trial. Her results are summarized in **Table 1**. Describe and explain the concentration of lactate in her muscle tissue after each trial. (4.4) K/U T/I A

Table 1

Trial	Number of push-ups
1	65
2	47
3	38
4	22

70. Examine **Table 2** showing a 5 min VO_2 max exercise event. Using your knowledge of exercise, explain why the following pH changes were observed in this athlete. (4.4) K/U T/I

Table 2

Time exercising at VO_2 max (min)	Blood pH
0	7.40
1	7.35
2	7.30
3	7.27
4	7.23
5 (stop)	7.20
6	7.30
7	7.35

71. Think of the waste that comes from your home, and choose one type of waste that you produce. Using your knowledge of anaerobic cellular respiration, design a system that could capture the potential energy in this waste and reduce your environmental impact. (4.2, 4.4) K/U T/I C A

Evaluation

72. Humans do not always have a steady supply of glucose. Therefore, the human body can use other fuels for aerobic cellular respiration. (4.2) K/U T/I
    (a) How do proteins and fats compare with glucose for ATP production?
    (b) How are proteins and fats broken down in preparation for respiration processes?
    (c) How would you use this information as fuel for a marathon?
73. Imagine that you have been sent by a team of scientists to examine a new life form. (4.2) K/U T/I
    (a) What are the first questions that you would try to answer about the physiology of this new life form?
    (b) What types of clues might you look for in the organism's environment to help you determine its metabolic pathways and food sources? Explain your reasoning.
74. A typical human cell uses about 1 million molecules of ATP per second. (4.2) T/I
    (a) Assuming that the human body contains 100 trillion cells, calculate how many molecules of ATP must be produced per second to meet this demand.
    (b) How many glucose molecules are equivalent to the amount of ATP you calculated in (a)?
    (c) What is the mass of the amount of glucose you calculated in (b)? (**Note:** Use 180 g/mol.)
75. Why can a diet that is high in fat cause weight gain? (4.3) T/I
76. You have been asked to design an environmentally friendly vehicle. You need to decide whether to use anaerobic cellular respiration, cellular respiration, or gasoline as the fuel for the engine. Which of these fuels would you use, and why? Use a Venn diagram to show your comparison of the three possible fuels. (4.2, 4.4) K/U T/I C A
77. In terms of entropy, how does the change in structure of ADP and ATP account for the release of chemical energy by ATP? (4.2) K/U T/I
78. (a) If you were a health and fitness specialist, what type of diet and exercise program would you recommend for a professional basketball player? Explain your reasoning.
    (b) How might your recommendation differ if it was for a professional body builder? (4.2) K/U T/I A
79. A scientist who is studying a wetland notices that the fish in the wetland die every autumn (**Figure 4**). Through field observations, the scientist finds that their death coincides with the smell of hydrogen sulfide, H_2S. (4.4) K/U T/I C A
    (a) What do you think the smell indicates?
    (b) What environmental factors would cause the smell?
    (c) Why do you think the smell occurs in the autumn?
    (d) Write a letter to the editor of a scientific journal to explain this phenomenon and what the residents need (or do not need) to be concerned about.

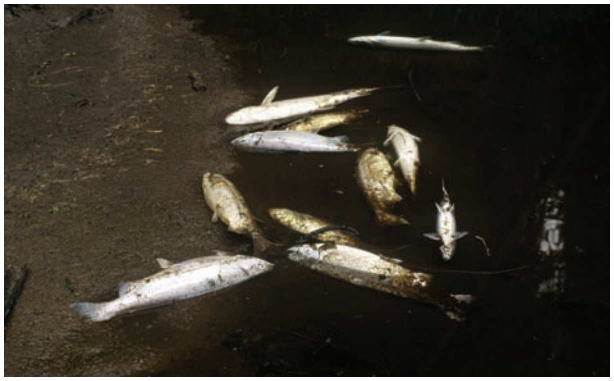


Figure 4

Reflect on Your Learning

80. In this chapter, you examined several different metabolic pathways. How do you think this knowledge will affect your choice of exercise and diet in the future? K/U T/I A
81. In this chapter, you learned that beetroot juice can improve the efficiency of mitochondria and increase endurance. What other foods do you think would improve the efficiency of mitochondria? Explain your reasoning. K/U T/I
82. Several potential careers were introduced in this chapter. Which one of these careers was especially interesting to you? Explain why. T/I
83. Which of the different metabolic pathways discussed in this chapter do you think is the most important to the environment? Explain your reasoning. K/U T/I A
84. Has your understanding of metabolism changed your view of dietary supplements? Explain. K/U T/I
85. Which section in this chapter did you find the most interesting? Did anything you learned surprise you? T/I

Research

WEB LINK

86. Use the Internet to investigate the difference between aerobic exercises and anaerobic exercises. Give several examples of each. K/U T/I

87. Many people use thermogenic supplements to help them lose weight. Conduct online research to answer the following questions: K/U T/I A
    (a) Based on your research and your understanding of energy metabolism, explain how thermogenic supplements work.
    (b) What risks are associated with using thermogenic supplements?
    (c) Would you recommend thermogenic supplements for an adult who wants to lose weight? Explain your reasoning.

88. Vitamin B_5 is needed for the synthesis of coenzyme A. It must be obtained from dietary sources because the body does not produce it. K/U T/I A
    (a) Conduct online research to learn more about the effects of vitamin B_5 deficiency, and share your findings with classmates.
    (b) How would a lack of vitamin B_5 influence the pathways of aerobic respiration?

89. Cyanide is poison that interferes with cellular respiration. K/U T/I C A
    (a) Conduct online research to find out about other "metabolic poisons" that act by interfering with the stages of aerobic cellular respiration.
    (b) Design an informative poster or pamphlet that could be used by a local health unit to help parents childproof their home.

90. Research the relationship between mitochondrial activity and the production of thermal energy in warm-blooded animals. Write a one-page report to summarize your findings. Your report should consider the following questions: K/U T/I C A
    (a) How is the electron transport chain used to generate thermal energy?
    (b) What is brown fat tissue? How does it differ in terms of its mitochondria? Why is it brown?
    (c) Why is brown fat more abundant in newborns and hibernating animals?

91. Research the physiological basis of cirrhosis of the liver. K/U T/I C
    (a) What is one cause of cirrhosis that is related to alcohol?
    (b) How does alcohol affect cellular respiration?
    (c) Design a poster that would help teenagers understand the dangers of alcohol consumption and cirrhosis to metabolism.

92. Conduct an online search to find a recipe for leavened (raised) bread, as well as a recipe for unleavened (flat) bread (**Figure 5**). K/U T/I A
    (a) Explain how the recipes differ.
    (b) Which ingredient is present in one recipe but not in the other recipe? Explain the significance of this missing ingredient.

Figure 5

93. You are part of a team of health experts who have been asked to host an event that will raise awareness about mitochondrial diseases. The tasks have been divided so that each of you is responsible for part of the event. Conduct online research and design a brief five-slide multi-media presentation that highlights the following:
    - the causes and symptoms of mitochondrial diseases
    - possible treatments and their side effects
    - community services and support that are available to people with mitochondrial diseases
    - the status of current research to find a cure K/U T/I C

94. Many treadmills and exercise bikes have a target heart rate (THR) indicator that tells users what heart rate they must reach in order to achieve their exercise goals (such as fat burning or cardio training). THR is calculated using a variety of factors and depends on the goals of exercise (fat burning will have a different THR than cardio training, for example). Use the Internet and other sources to research target heart rates for different types of training (i.e., exercise). Use your findings to prepare a pamphlet that you could give to your classmates who want to receive the most benefit from their workout. Use the following to help you prepare your pamphlet:
    - Identify the heart-rate ranges for at least three different types of training (e.g., fat burning).
    - Create a graph or other visual to show the THR for each type of training, according to age.
    - Explain why age must be taken into account when measuring heart rate.
    - Explain what aerobic capacity is and how it affects metabolic rate.
    - Explain why it is important to measure heart rate when performing exercise. K/U T/I C A

CHAPTER

5 Photosynthesis: The Energy of Life

KEY CONCEPTS

After completing this chapter you will be able to

- explain why photosynthesis takes place in the chloroplasts within a system of membranes
- describe chlorophyll as a photosynthetic pigment that captures light energy of specific wavelengths
- explain how light energy energizes electrons to produce ATP in the light-dependent reactions of photosynthesis
- outline how the Calvin cycle results in the production of simple carbon compounds that can be converted into glucose or used to build other molecules
- explain how some plants use alternative pathways to avoid the effects of photorespiration
- compare and contrast aerobic cellular respiration with photosynthesis, and describe the many applications of both processes

How Do Plants Convert Light Energy into Life's Energy?

Life abounds on planet Earth. Trillions of individual organisms have been growing, moving, and reproducing on Earth's surface for billions of years. From far out in space, Earth appears as an isolated pale blue dot illuminated by the Sun from a distance of 160 million kilometres. Up close, however, we see Earth's surface as a mix of land and water. Much of that land is covered by a living layer of green plants and is inhabited by millions of different species. Earth's great oceans are also rich with life—much of it microscopic and living near the surface. For scientists, these observations lead to two primary questions: What powers all this life? What is so special about the colour green? In this chapter, you will discover the answers to these questions.

You have learned how living organisms use cellular respiration and fermentation pathways to meet their energy needs. These pathways extract energy from the carbohydrates, proteins, and lipids in their food and convert it into energy stored in ATP. The food molecules themselves are produced by living organisms. Animals and other consumers obtain these food molecules by eating other organisms, while plants and other producers are able to make their own food molecules. But where does the energy in all of these food molecules come from in the first place?

The answer lies in the process of photosynthesis, where producers, such as green plants, and photosynthetic bacteria and protists convert light energy to chemical energy. Chlorophyll and other pigments actively capture the Sun's energy. This captured energy is then used to convert carbon dioxide and water into complex energy-rich molecules. It is this "fixing" of carbon into energy-rich organic compounds, via photosynthesis, that sustains almost all life on Earth. The total amount of carbon that is fixed into organic material is staggering—approximately 1.1×10^{14} kg of carbon each year. Land plants fix about half of this carbon, while the other half is fixed by phytoplankton—the photosynthetic micro-organisms that live in freshwater and marine environments.

In this chapter, you will learn the details of how photosynthesis works. While you will focus your attention on plants, you should note that the fundamental processes you will be studying are shared by all photosynthetic organisms.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. (a) All green plants and other photosynthetic organisms use the same green pigment—chlorophyll or a variation of chlorophyll. Suggest possible reasons for this shared characteristic.
   (b) What might this shared characteristic suggest about the properties of chlorophyll?
2. How might a plant's environment influence its ability to perform photosynthesis? Consider the needs of aquatic plants, desert plants, and plants that must survive with relatively low levels of light.
3. In the previous chapter, you explored the chemical pathways of aerobic respiration as well as their relationship to the structure of mitochondria. Speculate about the possible chemical pathways and cellular structures that might be needed for photosynthesis.

Mini Investigation

Observing Plant Pigments

Skills: Performing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

In this activity, you will use paper chromatography to separate the pigments in a plant leaf. Paper chromatography uses a liquid solvent to separate a mixture into individual components.

Equipment and Materials: chromatography paper; scissors; large test tube and test-tube rack; ruler; pencil; mature spinach leaf; coin; paper clip; one- or two-holed rubber stopper; chromatography solvent; UV light

1. Cut a strip of chromatography paper 2 cm shorter than the test tube, and wide enough to fit in the test tube without touching the sides. Cut off the corners at one end to make a point. Draw a pale line across the strip 2 cm from this end.
2. Place a spinach leaf over the pencil line. Roll the edge of the coin over the spinach leaf, pressing hard to crush a narrow line of leaf material onto the pencil line. Repeat this several times with a fresh part of the leaf so that you have a single dark green thin line on the paper (**Figure 1**).
3. Add chromatography solvent to the bottom of the test tube to a depth of approximately 2 cm.
4. Use a paperclip to hang the paper strip from the rubber stopper. Insert the hanging strip into the test tube so that the bottom of the strip just touches the solvent. Do not let the green pigment line reach the solvent.

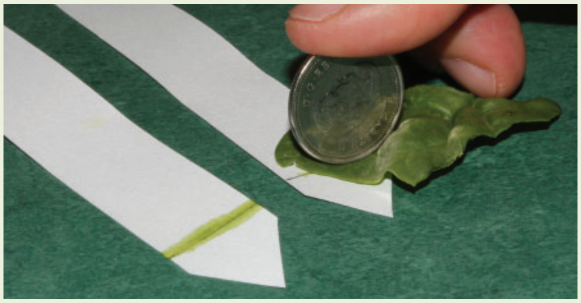


Figure 1

5. Remove the strip once the solvent has reached 3–4 cm from the top. Use the pencil to mark the end of the solvent.
6. Allow the strip to dry. Observe the strip under both bright natural light and UV light. Use the pencil to outline each "patch" of coloured pigment.

A. What did you observe as the solvent moved through the pigment line and up the strip? T/I

B. How many different pigments separated from each other? Describe their colours. T/I

5.1 Photosynthesis: An Introduction

photoautotroph an organism that makes its own food using energy from the Sun

Photosynthetic organisms make their own food using energy derived from the Sun. **Photoautotrophs** are the primary producers on Earth, converting light energy into chemical energy and using it to assemble complex organic molecules from simple inorganic raw materials (**Figure 1**). Producers use the organic molecules they create as energy sources for their own activities and as the organic building blocks of their own bodies. Producers also serve—directly or indirectly—as food sources for consumers, the organisms that live by eating other organisms. Consumers use some of the organic molecules obtained from producers to obtain energy, and some as building materials for their cells and body parts. This is analogous to a person using wood both as fuel for heating and cooking, and as a building material. Eventually, the bodies of both producers and consumers provide chemical energy and building materials for decomposers, which feed on dead and decaying organisms. Decomposers ultimately return simple inorganic molecules back into the soil, air, or water, making the inorganic molecules available once again to photosynthetic organisms.

It may seem that this cycling of matter through producers, consumers, and decomposers can continue indefinitely with no further input. However, recall the second law of thermodynamics: entropy increases with every energy transformation or chemical reaction. As a result, some useful free energy is lost at each stage of the cycle. Therefore, there must be a continual input of free energy from the Sun for life on Earth to continue. The pathway of photosynthesis is responsible for this vital task.

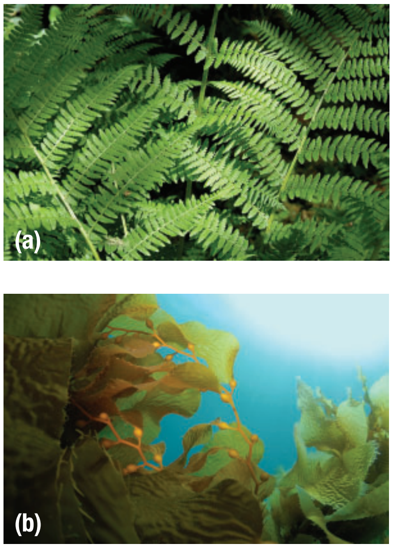


Figure 1 (a) Green plants and (b) kelp are examples of photoautotrophs.

The Two Stages of Photosynthesis

Photosynthesis has two distinct stages. The light-dependent reactions are directly associated with the absorption of photons of light. The light-independent reactions (called the Calvin cycle) do not require light themselves, but they are dependent on products of the light-dependent reactions (**Figure 2**).

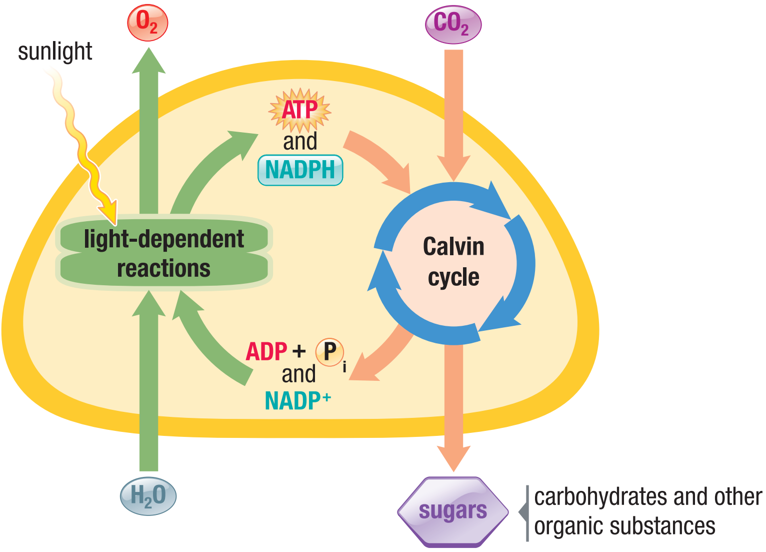


Figure 2 Both stages of photosynthesis occur in the chloroplasts of photosynthetic eukaryotes as well as in photosynthetic prokaryotes.

light-dependent reactions the first stage of photosynthesis, during which water molecules are split as light energy is absorbed and transformed into chemical energy in ATP and NADPH

During the **light-dependent reactions**, light energy is captured by pigment molecules and used to synthesize nicotinamide adenine dinucleotide phosphate (NADPH) and ATP. During this process, a water molecule is split and an electron transport chain transfers high-energy electrons to $NADP^+$ carrier molecules to establish a proton gradient across a membrane. Oxygen is generated when the water molecule is split and is released to the environment. Energy stored in the proton gradient is used to generate ATP.

In the **Calvin cycle**, the now high-energy electrons carried by NADPH and the energy stored in ATP molecules are used to convert CO_2 into high-energy organic compounds (Figure 2). This process is called CO_2 fixation. With the addition of electrons and protons (H^+), CO_2 is first converted to a simple 3-carbon carbohydrate. It is then used to synthesize larger molecules, such as glucose. Carbohydrates are the major end products of photosynthesis, but the reduced carbon produced by photosynthesis is also the source of the carbon backbone for a huge range of other molecules, including lipids and proteins. In fact, all the organic molecules of plants are assembled as direct or indirect products of photosynthesis.

Calvin cycle the second stage of the photosynthesis process that uses ATP and NADPH to convert CO_2 to sugars

The general chemical equation for photosynthesis is

$$6\ CO_2 + 6\ H_2O \xrightarrow{\text{light energy}} C_6H_{12}O_6 + 6\ O_2$$

This equation suggests that photosynthesis is simply the reverse reaction of aerobic cellular respiration. However, as you will soon learn, while there are important steps that mirror the respiration pathway, photosynthesis is not merely the citric acid cycle and glycolysis in reverse.

Research This

Experimenting with Jan Baptist van Helmont

Skills: Researching, Evaluating, Communicating

SKILLS HANDBOOK A4.1

Jan Baptist van Helmont (1579–1644) was a pioneer in chemistry and experimental methods. He was also one of the first scientists to study the processes that allow plants to grow. His famous willow tree experiment is the subject of this research activity.

1. Use the Internet and other sources to investigate van Helmont's famous willow tree experiment.

A. Describe the experiment that van Helmont performed. T/I
   (i) How long did his experiment take?
   (ii) Outline his experimental procedure, including the variables that he controlled and measured.
   (iii) How did his conclusions differ from the expected results?
   (iv) What source of mass did van Helmont not account for in his experiment?

B. Explain how van Helmont's experiments allowed scientists to gain information in a different manner, rather than simply making assumptions based on casual observations. T/I

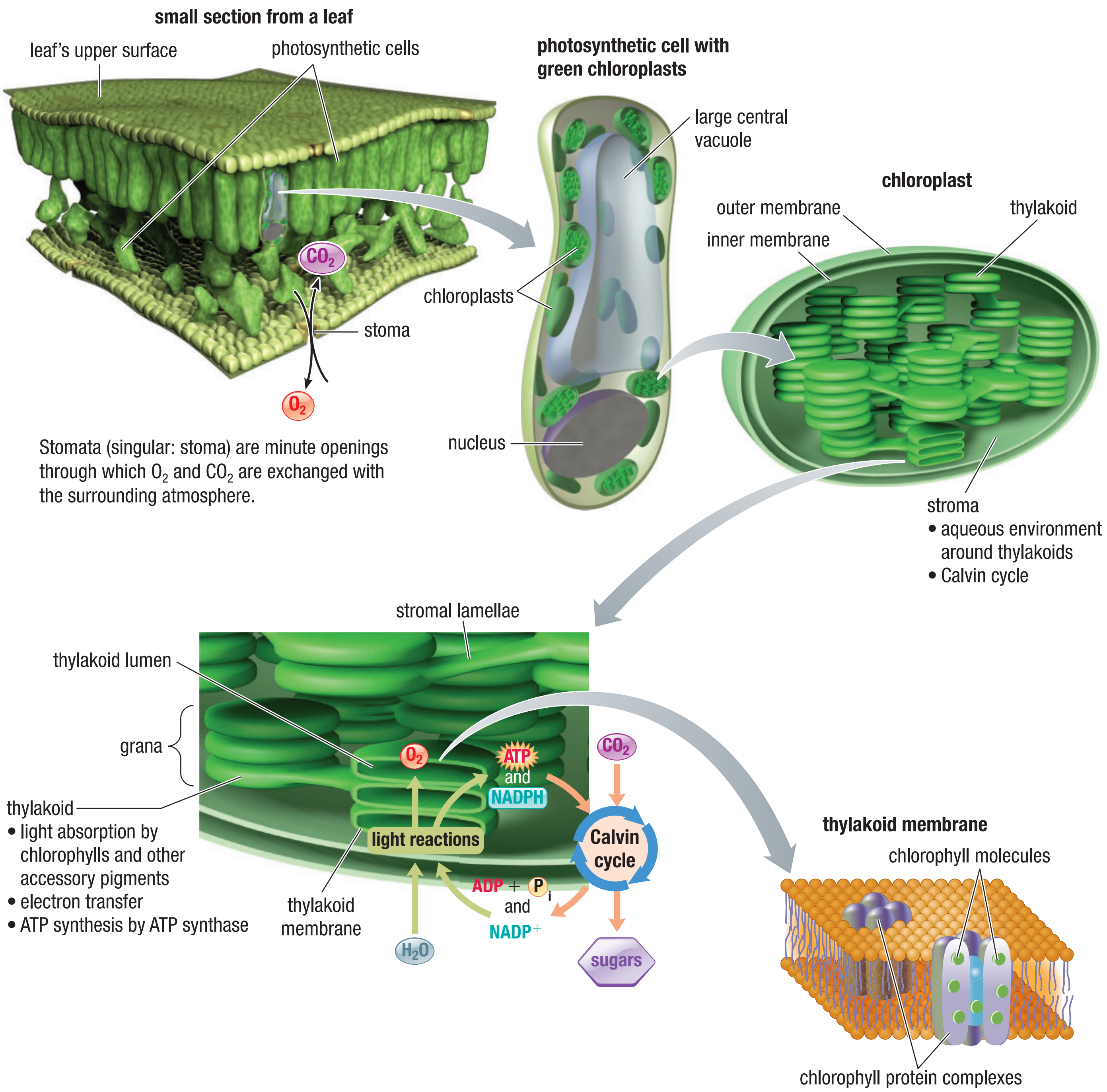
C. (i) How do his conclusions illustrate the challenge of designing experiments and accounting for all variables?
   (ii) How would you redesign van Helmont's experiment? T/I

D. Expand your Internet search to discover which scientist's experiments provided information on the role of CO_2 in photosynthesis. T/I

WEB LINK

Chloroplasts: Photosynthesis Machines

In photosynthetic eukaryotes, both the light-dependent reactions and the Calvin cycle take place within the chloroplast, an organelle formed from three membranes that define three distinct compartments (**Figure 3,** next page). An outer membrane covers the entire surface of the organelle, and a second, inner membrane lies just inside the outer membrane. The aqueous environment within the inner membrane is the stroma. The enzymes that catalyze the reactions of the Calvin cycle are found in the stroma of the chloroplast. Also within the stroma is the third membrane system, the thylakoid membranes, or thylakoids. The thylakoids form interconnected stacks of flattened discs called grana (singular: granum). The space enclosed by a thylakoid is called the thylakoid lumen. The thylakoid membrane is where the light-dependent reactions of photosynthesis occur. The thylakoid membrane also gives leaves their green colour, because the chlorophyll and other accessory pigments are embedded within it.



Stomata (singular: stoma) are minute openings through which O_2 and CO_2 are exchanged with the surrounding atmosphere.

Figure 3 The membranes and compartments of chloroplasts

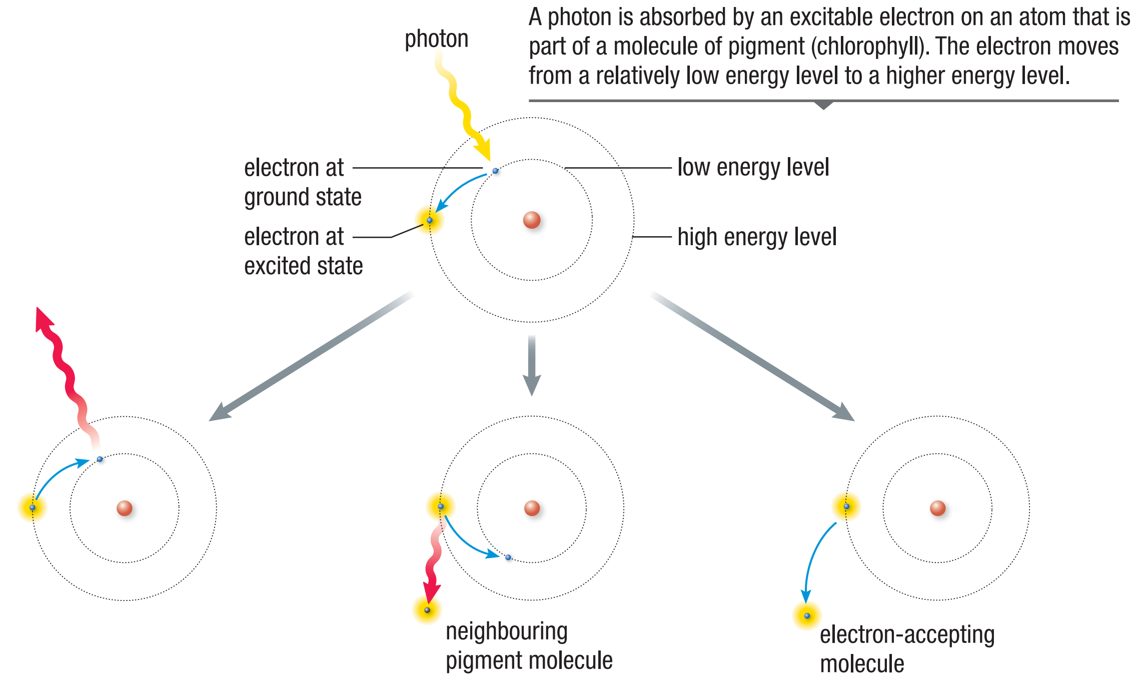
Capturing Light Energy

The ability to trap light energy and convert it into chemical energy requires a sophisticated photochemical apparatus that is unique in biology. This section describes the components of the light-dependent reactions that are located in the thylakoid membranes. There are two points about light and pigment molecules that are important in photosynthesis. First, the absorption of a photon by a pigment molecule excites a single electron, moving it from a low energy, or ground state, to a higher energy, or excited state. Second, the difference between the energy level of the ground state and the energy level of the excited state must be equivalent to the energy of the photon of light that was absorbed. If the energies are not equivalent, the photon cannot be absorbed by the pigment.

Following light absorption, there are three possible outcomes for the excited electron within a pigment molecule. The relative probability of each outcome that takes place depends on the environment surrounding the pigment molecules, including the presence of other molecules.

In the first possible outcome, the excited electron simply returns to its ground state (**Figure 4(a)**). Its energy is released as either thermal energy or fluorescence. Fluorescence is the emission of light of a longer wavelength (lower energy) than the absorbed light. Fluorescence emits lower energy because a small amount of the energy of the photon that was initially absorbed is always lost as thermal energy. Remember that energy transformations are never 100 % efficient. In the second possible outcome, the energy of the excited electron is transferred to an electron in a neighbouring pigment molecule (**Figure 4(b)**). This now high-energy electron in the second pigment molecule is excited, and the original electron returns to its ground state. This requires the two molecules to be very closely and precisely aligned with one another. In the third possible outcome, the excited-state electron may itself be transferred to a nearby electron-accepting molecule (**Figure 4(c)**). This last outcome is one of the most important steps in photosynthesis—the energizing and transferring of an electron. In photosynthesis, the key electron-accepting molecule is called a **primary electron acceptor**.

primary electron acceptor a molecule capable of accepting electrons and becoming reduced during photosynthesis


photon
A photon is absorbed by an excitable electron on an atom that is part of a molecule of pigment (chlorophyll). The electron moves from a relatively low energy level to a higher energy level.
electron at ground state
electron at excited state
low energy level
high energy level
neighbouring pigment molecule
electron-accepting molecule

(a) The electron returns to its ground state by emitting a less energetic photon (fluorescence) or by releasing energy as thermal energy.

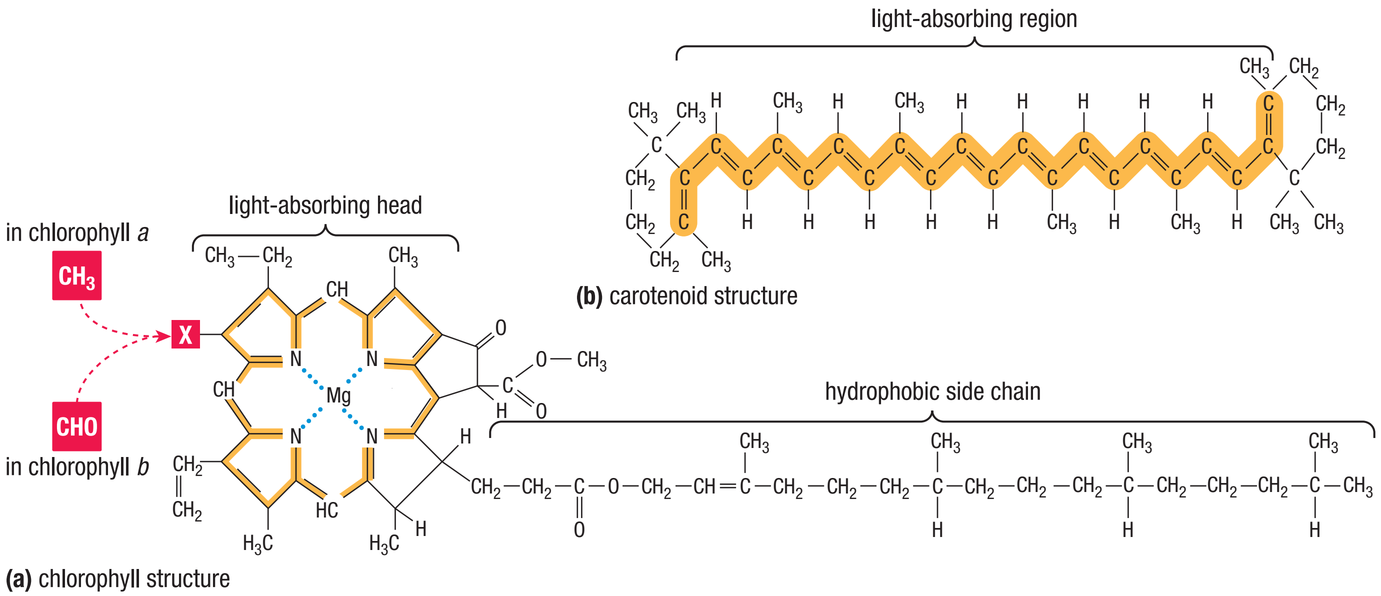
(b) The electron returns to its ground state, and the energy released is transferred to a different electron in a neighbouring pigment molecule.

(c) The high-energy electron is accepted by an electron-accepting molecule, the primary acceptor.

Figure 4 There are three possible fates of an excited-state electron.

How Chlorophylls and Carotenoids Cooperate in Light Absorption

Chlorophylls are the major photosynthetic pigments in plants, green algae, and cyanobacteria. The most dominant types of chlorophylls are chlorophyll *a* and chlorophyll *b*, which have slightly different structures (**Figure 5(a)**, next page). In photosynthetic prokaryotes other than cyanobacteria, closely related molecules called bacteriochlorophylls carry out the same functions. The second major group of photosynthetic pigments is the carotenoids (**Figure 5(b)**, next page).



(a) chlorophyll structure

(b) carotenoid structure

Figure 5 (a) Chlorophylls *a* and *b* differ only in the side group attached at the X. Light-absorbing electrons are distributed among the bonds shaded in orange. (b) In carotenoids, the electrons that absorb light are distributed in a series of alternating double and single bonds in the backbone of the pigment.

antenna complex a cluster of light-absorbing pigments embedded in the thylakoid membrane able to capture and transfer energy to special chlorophyll *a* molecules in the reaction centre

reaction centre a complex of proteins and pigments that contains the primary electron acceptor

During photosynthesis, chlorophyll *a* becomes oxidized and donates an electron to a primary electron acceptor. Carotenoids and chlorophyll *b* are referred to as accessory pigments because after light absorption, they transfer this excitation energy to molecules of chlorophyll *a*. This set of accessory pigments, referred to as an **antenna complex**, captures light energy and transfers it to a chlorophyll *a* molecule and the primary electron acceptor in the **reaction centre** (**Figure 6**).

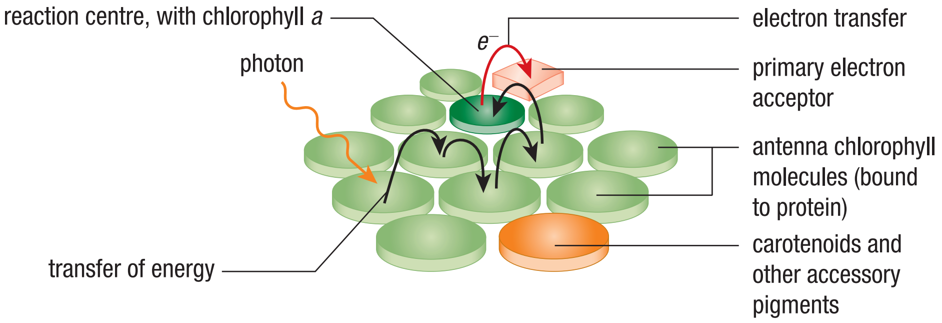

reaction centre, with chlorophyll a
photon
e⁻
electron transfer
primary electron acceptor
antenna chlorophyll molecules (bound to protein)
carotenoids and other accessory pigments
transfer of energy

Figure 6 The antenna complex captures light energy and transfers it to the reaction centre.

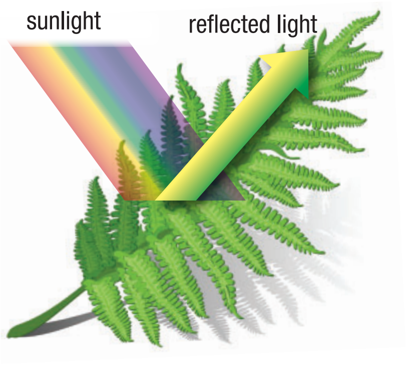


Figure 7 Leaves appear green because chlorophylls reflect green and some yellow light but absorb wavelengths in other parts of the spectrum.

absorption spectrum a plot of the amount of light energy of various wavelengths that a substance absorbs

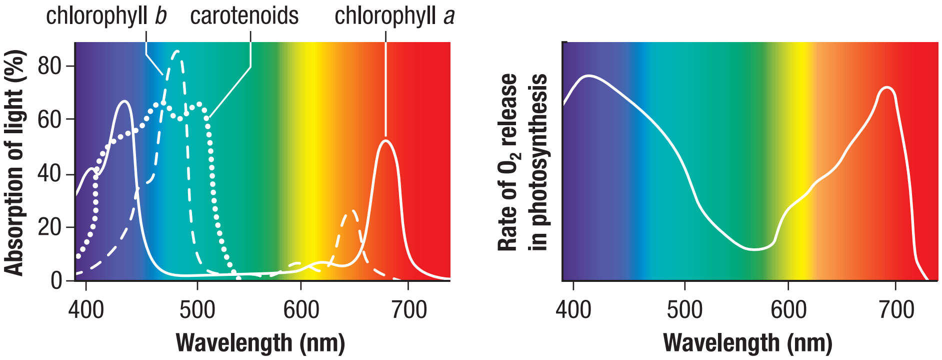
A pigment molecule does not absorb all wavelengths of light. The wavelengths that are not absorbed are transmitted (pass through the object) or reflected. The green and yellow light is reflected, making the plant leaves containing chlorophyll *a* appear green (**Figure 7**). This reflected light is what gives the pigment its distinctive colour. You can determine which wavelengths of light a pigment absorbs by producing an **absorption spectrum**—a plot of the absorption of light as a function of wavelength. An absorption spectrum is produced using an instrument called a spectrophotometer, which analyzes a sample of the pigment. For example, chlorophyll *a* absorbs strongly blue and red light but does not absorb green or yellow light. Each pigment absorbs light over a different range of wavelengths (**Figure 8(a)**, next page). Note that carotenoids do not absorb light waves in the red and yellow range. These light waves are reflected back to your eyes as the colour orange. As you might guess from the name, carotenoids are found in carrots. There is a wide variety of other pigments, which give rise to the diversity of colours found in plant life around the world. The vivid colours of fall foliage appear when the dominant green chlorophyll degrades from the leaves and other pigments are revealed. These pigments reflect colours other than green.

Photosynthesis depends on the absorption of light by chlorophylls and carotenoids acting in combination. The effectiveness of light of various wavelengths in driving photosynthesis is plotted as an **action spectrum** for photosynthesis (**Figure 8(b)**). The action spectrum is usually determined by using a suspension of chloroplasts or algal cells and measuring the amount of O_2 released by photosynthesis at different wavelengths of visible light. If an action spectrum for a physiological phenomenon matches the absorption spectrum of a pigment, it is very likely that the two are linked.

action spectrum a plot of the effectiveness of light energy of different wavelengths in driving a chemical process

UNIT TASK **BOOKMARK**

You can use what you have learned about the absorption spectrum and the action spectrum to design your Unit Task investigation on page 252.



(a) absorption spectra **(b)** action spectrum

Figure 8 These graphs show (a) the absorption spectra of the photosynthetic pigments, chlorophylls *a* and *b* and carotenoids, and (b) the action spectrum in higher plants, representing the combined effects of chlorophylls and carotenoids. Notice how the spectra match.

Theodor Engelmann produced one of the first action spectra in 1882. He used only a light microscope and a glass prism to determine which wavelengths of light were most effective for photosynthesis. Engelmann placed a strand of a green alga, *Spirogyra*, on a glass microscope slide, along with water containing aerobic bacteria (bacteria that require oxygen to survive). He adjusted the prism so that it split a beam of light into its separate colours, which spread like a rainbow across the strand (**Figure 9**). After a short time, he noticed that the bacteria had begun to cluster around the algal strand in the regions where oxygen was being released in the greatest quantity—the regions in which photosynthesis was proceeding at the greatest rate. Those regions corresponded to the colours (wavelengths) of light that were being absorbed most effectively by the alga. The largest clusters were under the blue and violet light at one end of the strand and the red light at the other end. Very few bacteria were found under the green light. This provided compelling evidence of the influence of different colours of light on photosynthesis.

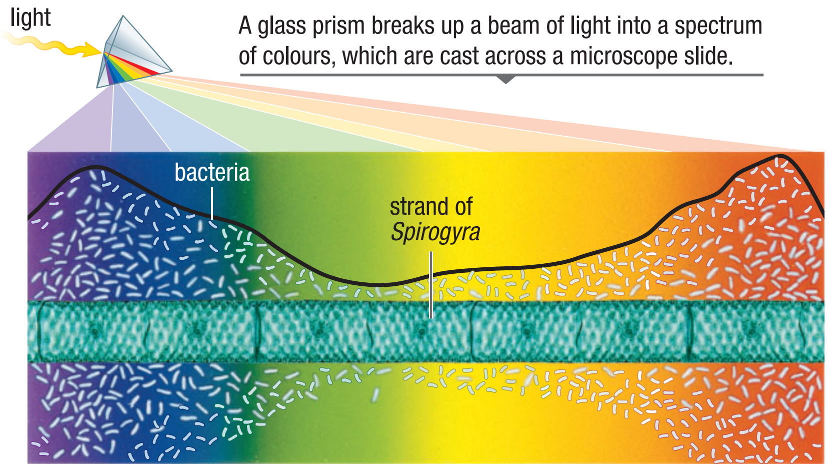

light
A glass prism breaks up a beam of light into a spectrum of colours, which are cast across a microscope slide.
bacteria
strand of *Spirogyra*

Figure 9 Engelmann's 1882 experiment revealed the action spectrum of light used in photosynthesis by *Spirogyra*, a green alga. The bacteria clustered in areas where the most oxygen was produced. Oxygen is a product of photosynthesis.

Pigments and Photosystems

Pigment molecules are bound very precisely to a number of different proteins. They do not float freely within the thylakoid membranes. These pigment proteins are organized into photosystems. Each photosystem is composed of the large antenna complex (also called a light-harvesting complex) of proteins and some 250 to 400 pigment molecules surrounding a central reaction centre. The reaction centre of a photosystem comprises a small number of proteins, each bound to a pair of specialized chlorophyll *a* molecules, as well as the primary electron acceptor (**Figure 10**). Light energy absorbed by the antenna complex is transferred to specialized chlorophyll molecules in the reaction centre. Light energy is converted to chemical energy when a reaction centre chlorophyll donates an electron to the primary electron acceptor. This electron, in turn, is passed along an electron transport chain.

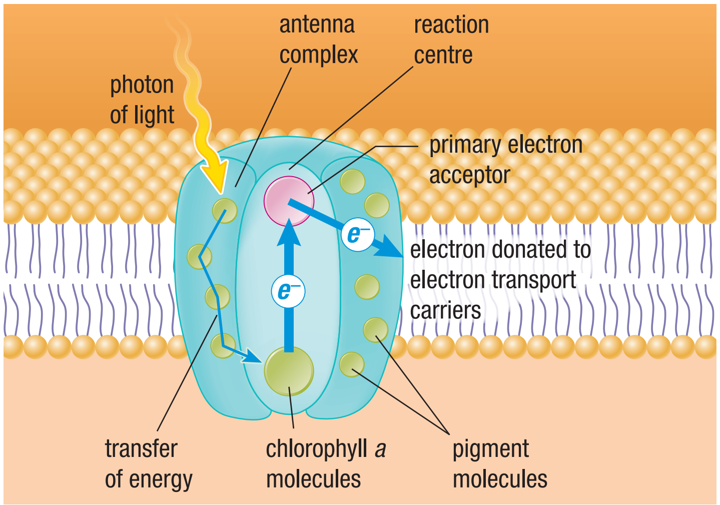

antenna complex
reaction centre
photon of light
primary electron acceptor
e⁻
electron donated to electron transport carriers
e⁻
transfer of energy
chlorophyll *a* molecules
pigment molecules

Figure 10 A photosystem composed of a light-harvesting antenna complex and a reaction centre

photosystem I a collection of pigment proteins that includes chlorophyll *a* and absorbs light at the 700 nm wavelength

photosystem II a collection of pigment proteins that includes chlorophyll *a* and absorbs light at the 680 nm wavelength

There are two kinds of photosystems: photosystem I and photosystem II (also called PSI and PSII). The reaction centre of **photosystem I** contains specialized chlorophyll *a* molecules, which are known as P700 molecules (P = pigment) because they absorb light optimally at a wavelength of 700 nm. The reaction centre of **photosystem II** contains P680 chlorophyll *a* molecules, which absorb light optimally at a wavelength of 680 nm. P700 and P680 are structurally identical to other chlorophyll *a* molecules. Their specific patterns of energy absorption result from interactions with proteins in the photosystem. The photosystems were numbered based on the order they were discovered. However, in photosynthesis, the actions of photosystem II occur before those of photosystem I.

Photosystems trap photons of light and use the energy to energize a chlorophyll *a* molecule in the reaction centre. The chlorophyll *a* molecule is then oxidized as it transfers a high-energy electron to the primary electron acceptor. High rates of oxidation-reduction can be achieved within the photosystem when the pigments in the large antennae complex absorb the light of a range of wavelengths and efficiently transfer the energy to the reaction centre. In the sections that follow, you will learn how the high-energy electrons generated by photosystems can be used to drive ATP synthesis and to assemble the high-energy organic molecules that plants and animals use as food. You will also learn how these processes might be used to develop new light-gathering and energy-producing technologies.

Investigation **5.1.1**

Light and Photosynthesis (p. 241)
In Investigation 5.1.1, you will explore the products of photosynthesis and the importance of light in their creation.

5.1 Review

Summary

- Producers use photosynthesis to convert light energy into chemical energy, which is then stored and used to assemble energy-rich organic molecules that are used by producers and consumers.
- Photosynthesis has two stages—the light-dependent reactions and the light-independent reactions (the Calvin cycle).
- The light-dependent reactions take place in the thylakoid membranes of the chloroplasts. Energy captured during the light-dependent reactions is used to synthesize NADPH and ATP.
- The Calvin cycle takes place in the stroma of the chloroplasts. It uses NADPH and ATP to convert carbon dioxide into simple carbohydrates.
- Chlorophylls, carotenoids, and other pigments absorb light energy during photosynthesis. Different pigments absorb light of different wavelengths, as shown by their absorption spectra. Light that is not absorbed is reflected. This reflected light gives pigments their colour.
- The action spectrum of photosynthesis in green plants is highest in the red and blue regions of the spectrum.
- Pigments, including chlorophylls and carotenoids, are organized into two types of photosystems: photosystem I and photosystem II. Each photosystem contains a reaction centre surrounded by an antenna complex that helps capture photons of light energy and energize electrons.

Questions

1. Why are photoautotrophs considered to be primary producers? K/U
2. Draw a labelled diagram that illustrates the relationship between the two stages of photosynthesis. Refer to your diagram to explain why these stages are considered interdependent. K/U C
3. Use a diagram to explain the relationship between the absorption of light energy and electron energy levels within an atom. Describe the three possible fates of an electron after it has jumped to a higher energy state. K/U C
4. Certain marine algae are able to live in low light, at depths of more than 100 m. These algae appear almost black deep under water, but usually appear red when brought to the surface. T/I
   (a) Would you expect these species to contain more or less chlorophyll than green algae? Why?
   (b) Would you expect these species to perform photosynthesis more efficiently under a green light source or a red light source? Explain your reasoning.
   (c) Things tend to look bluish underwater because water absorbs red light more effectively than blue light. How might this fact help account for the characteristics of the deep-water species of algae?
5. What are the thylakoids? Why are they important for photosynthesis? K/U
6. Write a series of steps that could be used as an experimental procedure for Engelmann's famous investigation that revealed the action spectrum of a living alga. T/I C
7. Compare an absorption spectrum of a pigment with the action spectrum for photosynthesis. K/U
8. Sketch a graph that shows what you would expect to be the overall action spectrum of the main pigments in the leaves in **Figure 11**. Explain your reasoning. C A

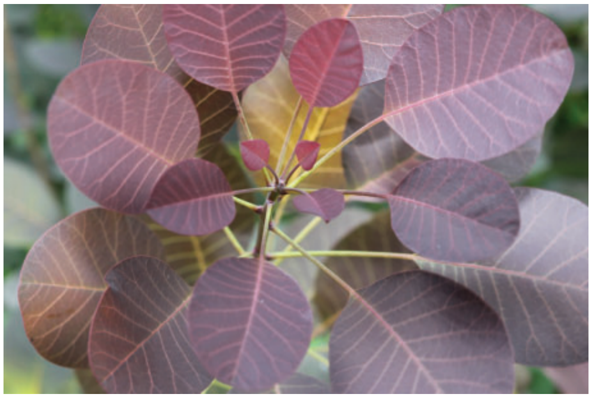


Figure 11

5.2 Pathways of Photosynthesis

Solar energy is the most abundant and widespread source of energy on Earth. In a single day, enough solar energy strikes Earth's surface to supply all human energy needs for 55 years. With such an abundant supply, scientists are researching and developing technologies to capture and use sunlight more efficiently to meet our growing energy demands. In fact, life on Earth evolved a pathway to harness this same energy source to meet its needs—a pathway living organisms have been using for well over 2 billion years.

This section examines the details of this extraordinary pathway. It will focus on how eukaryotes carry out photosynthesis in chloroplasts inside specialized photosynthetic cells. Keep in mind that these same chemical processes occur in photosynthetic prokaryotes, even though they do not have chloroplasts and other specialized structures that eukaryotes have. In prokaryotes, the photosynthesis reactions occur both in the cytosol and along folds in the cell membrane (**Figure 1**).

Figure 1 Although they do not have chloroplasts, prokaryotes like these cyanobacteria photosynthesize using the same chemical processes that eukaryotes use.

Light-Dependent Reactions

Photosystem II and photosystem I are the two light-capturing complexes used by most photoautotrophs. As in all electron transport systems, the electron carriers of the photosynthetic system consist of non-protein organic groups that alternate between being oxidized and being reduced as electrons move through the system. The carriers include compounds that are similar in structure and function to those in mitochondrial electron transport chains.

Photosystem II

As life emerged on Earth, it began to substantially change the environment. Earth's early atmosphere may have consisted of as little as 3 % oxygen gas and as much as 10 % carbon dioxide. We know that the composition of today's atmosphere is 21 % oxygen and only 0.04 % carbon dioxide. When simple organisms began using photosynthesis as a way to store energy in chemical compounds, they used water as their source of hydrogen atoms and their electrons. A by-product of this process was oxygen gas. As early photosynthetic organisms flourished, they generated an abundance of oxygen gas that accumulated in the atmosphere. This oxygen enabled the evolution of the rich diversity of aerobic life forms that we see on Earth today. CAREER LINK

The splitting of water into electrons, protons, and oxygen gas occurs in photosystem II. When a photon of light strikes the antenna complex, it is absorbed and its energy is transferred to the molecule P680, and one of its electrons changes from the ground state to an excited state, resulting in the energized molecule P680* (**Figure 2(a),** next page). The excited electron is then transferred to the primary acceptor molecule, which becomes negatively charged, while the P680 now carries a positive charge (**Figure 2(b)**, next page).

The resulting positive ion $P680^+$ is now extremely electronegative and can exert forces strong enough to remove an electron from a molecule of water! $P680^+$ is the strongest oxidant known in biology. The reduction of $P680^+$ to P680 by electrons from water is facilitated by an enzyme subunit of photosystem II called the water-splitting complex. This complex is inside the thylakoid membrane, facing the lumen.

Driven by this powerful electronegative pull, the water-splitting complex oxidizes a molecule of water, passing an electron to the $P680^+$ to make it neutral again (**Figure 2(c)**, next page). The acceptor molecule also transfers an electron to a molecule of plastoquinone (PQ) and becomes neutral, allowing the photon absorption process to start all over again. Note that this entire process occurs twice for each water molecule that is completely oxidized.

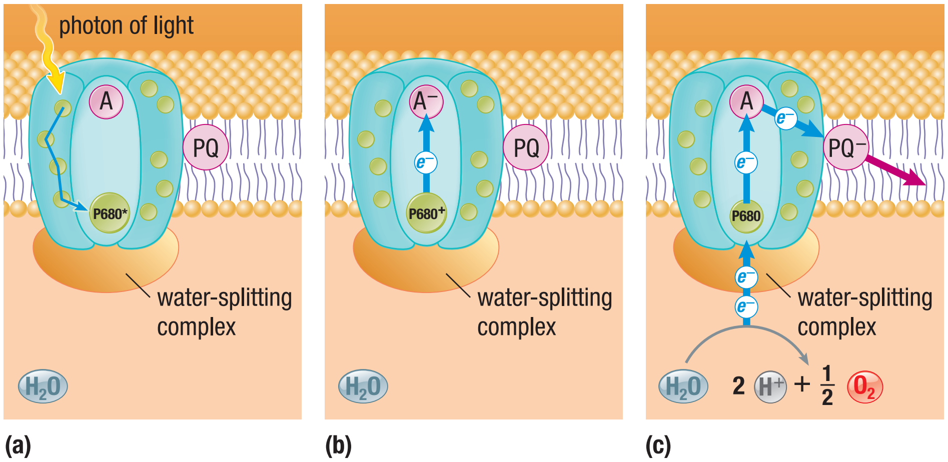


Figure 2 (a) The actions of photosystem II begin when a photon energizes an electron in P680, forming P680*. (b) The energized chlorophyll (P680*) then transfers the high-energy electron to acceptor A in the reaction centre. P680 is now positively charged. (c) The positive $P680^+$ ion then oxidizes water, and the high-energy electron is transferred from the reaction centre to the carrier molecule plastoquinone (PQ). This process releases both oxygen gas and protons into the lumen.

Linear Electron Transport and ATP Synthesis

The first steps in the electron transport chain within the thylakoid membrane involve the transfer of the high-energy electron to the primary acceptor and then to plastoquinone (PQ). Here, the light energy that is transferred to the electrons is used to generate a proton gradient. At the end of the electron transport chain, a second photosystem energizes the electrons a second time. The high-energy electrons can then be transferred to NADPH carrier molecules. The major steps of this electron transport system are illustrated in **Figure 3** and described below.

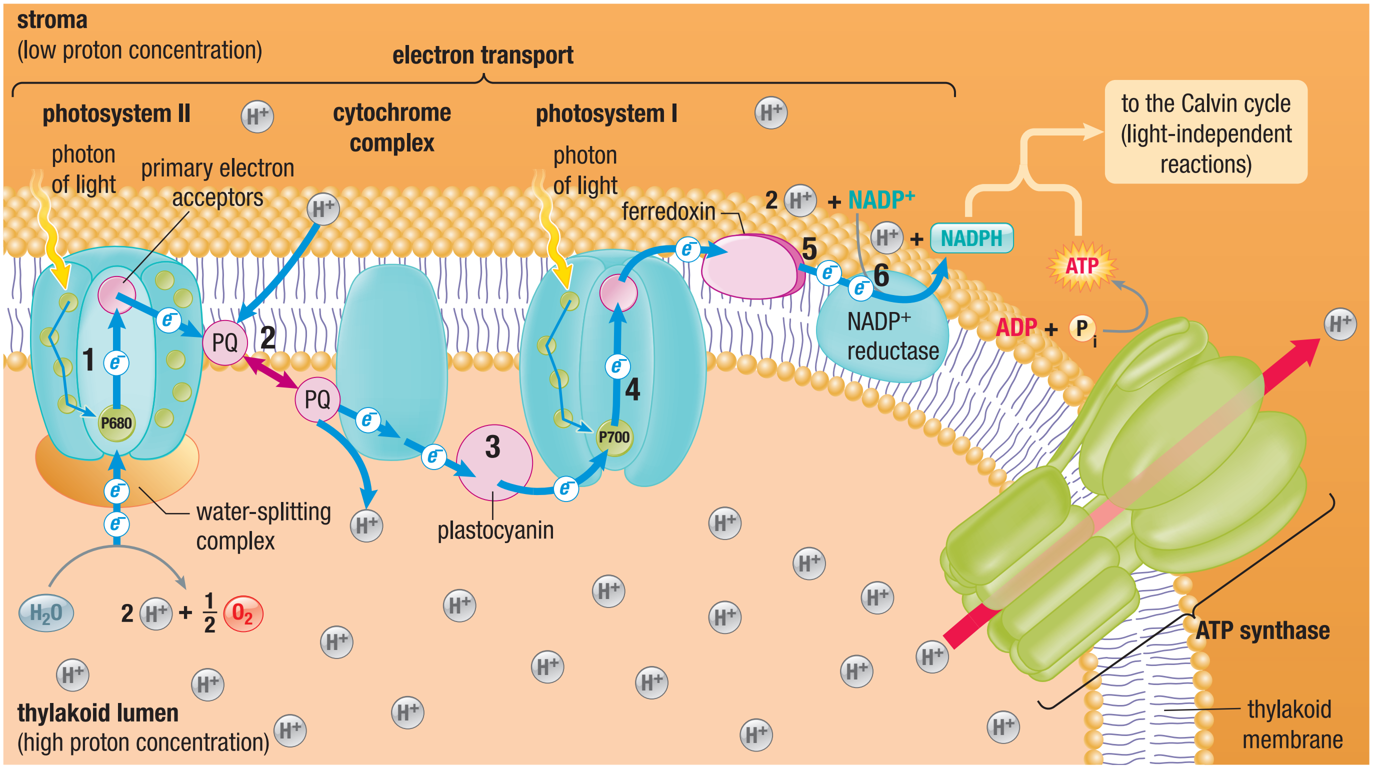


Figure 3 This model of the eukaryotic thylakoid membrane illustrates the major protein and redox cofactors required for non-cyclic electron transport and ATP synthesis by chemiosmosis. The four major protein complexes are photosystem II, the cytochrome complex, photosystem I, and ATP synthase. The blue arrow illustrates the pathway of electron transport.

1. **Oxidation of P680:** The absorption of light energy by photosystem II results in the formation of an excited-state P680 (P680*) molecule. This molecule is rapidly oxidized, transferring a high-energy electron to the primary acceptor.
2. **Oxidation-reduction of plastoquinone:** From the primary acceptor, the electrons transfer to plastoquinone (PQ), which moves through the lipid bilayer and acts as an electron shuttle between photosystem II and the cytochrome complex. As plastoquinone accepts electrons from photosystem II, it also gains protons (H^+) from the stroma. When PQ donates electrons to the cytochrome complex, it also releases protons into the lumen, increasing the proton concentration there.
3. **Electron transfer from the cytochrome complex and shuttling by plastocyanin:** From the cytochrome complex, electrons pass to the mobile carrier plastocyanin, which shuttles electrons from the cytochrome complex to photosystem I.
4. **Oxidation-reduction of P700:** When a photon of light is absorbed by photosystem I, an electron is excited and P700* forms. The P700* chlorophyll transfers its electron to the primary electron acceptor of photosystem I, forming $P700^+$. $P700^+$ can now act as an electron acceptor and is reduced back to P700 by the oxidation of plastocyanin.
5. **Electron transfer to $NADP^+$ by ferredoxin:** The first electron from P700* is transported by a short sequence of carriers within photosystem I. It is then transferred to ferredoxin, an iron-sulfur protein. The oxidation of ferredoxin results in the transfer of the electron to $NADP^+$, reducing it to NADP.
6. **Formation of NADPH:** A second electron is transferred to NADP by another molecule of ferredoxin. This second electron and a proton (H^+) from the stroma are added to NADP by the $NADP^+$ reductase to form NADPH. NADPH is now carrying two high-energy electrons. The concentration of protons in the stroma decreases as a result of this NADPH formation. Along with the movement of protons from stroma to lumen by plastoquinone and the splitting of water into protons, these three processes create a much higher proton concentration inside the lumen than outside in the stroma.

This pathway is referred to as linear (or non-cyclic) to distinguish it from an alternative process in which electrons are not passed on to NADPH. The proton gradient is used to generate ATP with the same kind of ATP synthase complexes found in mitochondrial membranes.

CHEMIOSMOTIC SYNTHESIS OF ATP

Recall from Chapter 4 that during cellular respiration, a proton gradient across a membrane is used as a source of energy to generate ATP by chemiosmosis. In the electron transport of photosynthesis just described, a similar proton gradient is established across the thylakoid membrane by three mechanisms (**Figure 4,** next page).

1. Protons are taken into the lumen by the reduction and oxidation of plastoquinone as it moves from photosystem II to the cytochrome complex and back again.
2. The concentration of protons inside the lumen is increased by the addition of two protons for each water molecule that is split in the lumen.
3. The removal of one proton from the stroma for each NADPH molecule formed decreases the concentration of protons in the stroma outside the thylakoid.

The result of these three mechanisms is a substantial proton gradient across the membrane. The higher concentration of protons inside the membrane creates a substantial proton-motive force that drives protons out of the lumen, back into the stroma. However, the thylakoid membrane allows protons to pass out into the stroma only through the pores in the protein complexes of ATP synthase, which are embedded in the membrane (Figure 4). This process, called chemiosmosis, is the same process that occurs in cellular respiration. The chloroplast's ATP synthase is, in fact,

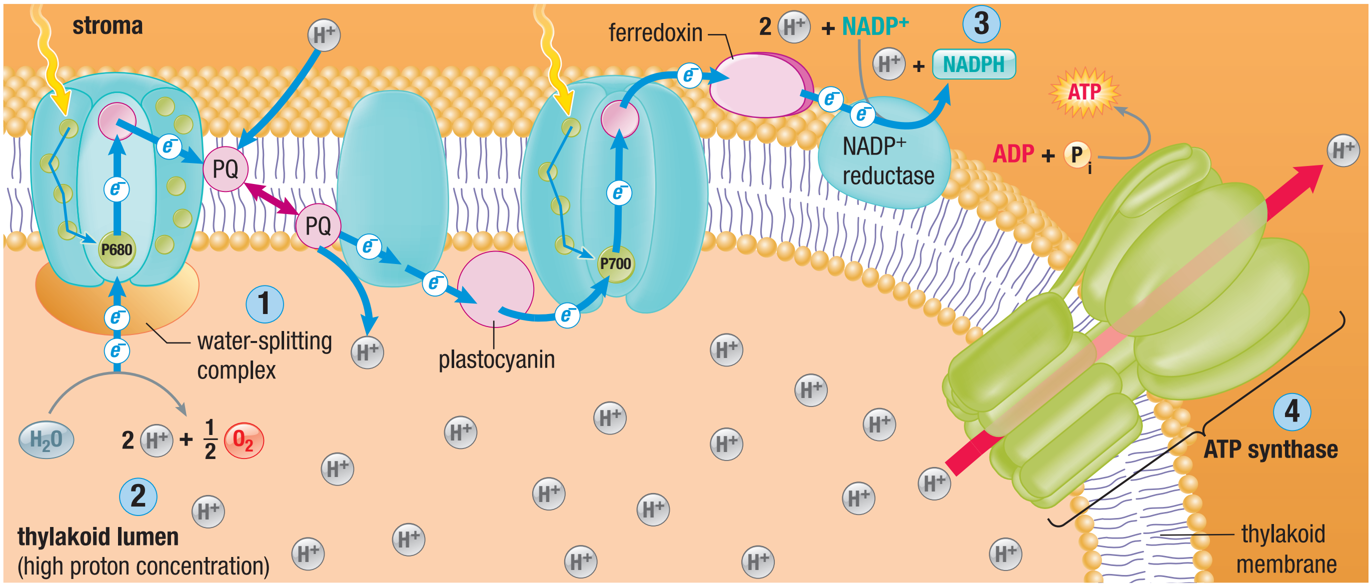


Figure 4 (1) A proton gradient is established by the carrying of protons across the membrane by PQ, (2) by the releasing of protons into the lumen during the oxidation of water, and (3) by the removal of protons from the stroma during the reduction of $NADP^+$. (4) ATP is then synthesized as protons move through the ATP synthase complex.

identical to the ATP synthase used in cellular respiration. As protons move through the channels in the ATP synthase, some of their free energy is captured and used to synthesize ATP from ADP and P_i.

THE ROLE OF LIGHT ENERGY

All electron transport chains operate by electrons being pulled spontaneously "downhill" from molecules with high-energy electrons (molecules that are easily oxidized) to molecules with progressively stronger attractions to electrons (molecules that are more electronegative). In mitochondrial respiration, the electron flow is "downhill" from high-energy NADH to very electronegative O_2. In photosynthesis, electron transport occurs by the same principle. The electron transport chain in respiration begins with high-energy NADH and finishes with low-energy H_2O. The opposite occurs in the electron transport chain in photosynthesis, which begins with low-energy H_2O and ends with high-energy NADPH. Therefore, to drive photosynthetic electron transport, low-energy electrons in water must be given enough potential energy to establish a proton gradient and enough energy to form NADPH. As you have seen, this dual function can be accomplished by the combined actions of photosystems I and II.

Figure 5 (next page) is a representation of the energy level changes that occur as electrons move along the electron transport chain of photosynthesis. First, by absorbing a photon of light, an electron in a P680 chlorophyll molecule of photosystem II gets excited and moves farther away from its nucleus. This high-energy electron is now held much less strongly by the P680* chlorophyll molecule. This enables the electron to be transferred to the primary electron acceptor.

A series of redox reactions follows, beginning with the oxidation of the acceptor molecule by plastoquinone and ending with the oxidation of plastocyanin by photosystem I. Each of these steps results in a small decrease in the free energy of the electron as oxidizing agents establish a stronger and stronger force of attachment to the electron. As you saw in Figure 4, these first steps released enough free energy to help establish a proton gradient across the thylakoid membrane. However, the electron is now bound to the strongly electronegative P700 chlorophyll molecule in photosystem I.

At this point, the primary acceptor of photosystem I is unable to pull away the strongly held low-energy electron from P700. This is overcome when photosystem I

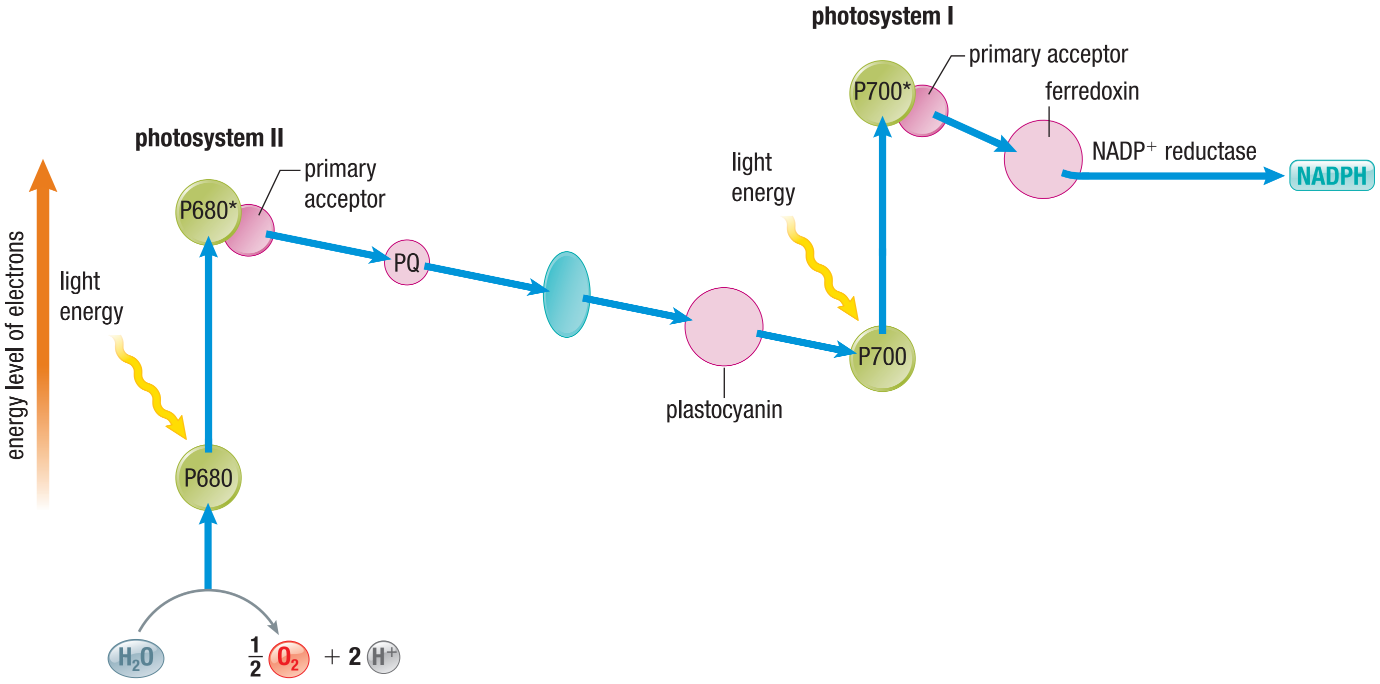


Figure 5 In the electron transport chain of the light-dependent reactions, the energy level of the electrons is increased dramatically by the light-absorbing actions of both photosystems II and I. The high-energy electrons at the end of the electron transport chain ultimately produce NADPH.

absorbs a photon of light, producing P700*. As was the case in photosystem II, the electron gains energy as it moves farther away from its nucleus. Since the electron is held less strongly it can be transferred to the acceptor molecule and along a second short redox pathway to $NADP^+$, which takes final possession of this high-energy electron.

Thus, two photons of light—one absorbed by photosystem II and another absorbed by photosystem I—are required to span the energy difference between H_2O and NADPH. Note that two electrons must be transported for every one molecule of NADPH produced. The conceptual chart shown in Figure 5 is sometimes referred to as the "Z scheme" because of the overall shape of the energy path of the electrons.

In respiratory electron transport, the electron flow is spontaneous from NADH to O_2, producing H_2O. By comparison, in photosynthetic electron transport, the electron flow is essentially the opposite, from H_2O to $NADP^+$. This electron flow does not occur spontaneously but must be boosted twice through the absorption of light energy.

Consider a physical analogy to the chemical pathway in Figure 5. Imagine that a cyclist travels along a path over two hills. The cyclist begins at the bottom of the first hill and must work hard, expending energy, to get to the top. Having reached the top of this hill, he stops pedalling and spontaneously coasts downhill a short distance, releasing a small amount of energy. Before getting back down to his original level, however, he comes to the base of another hill and must once again expend energy to climb. The top of this second hill is even higher than the first. At the top of the second hill, he starts to coast downhill again. The bottom of the second hill is higher than the start of the first hill. In this analogy, the energy to climb uphill is supplied by the cyclist rather than photons of light, but as in photosynthesis, the downhill parts of the pathway can happen spontaneously as energy is released.

LINEAR ELECTRON TRANSPORT—A BALANCE SHEET

You know that passing a single electron through the electron transport chain from photosystem II to $NADP^+$ requires two photons of light: one photon absorbed by photosystem II and a second photon absorbed by photosystem I. You also know that this process began with the oxidation of water and the production of oxygen gas. How many photons need to be absorbed by the photosynthetic apparatus to produce a single molecule of O_2? First, write out a balanced equation. This shows that two molecules of H_2O must be oxidized to energize and remove four electrons:

$$2\ H_2O \rightarrow 4\ H^+ + 4\ e^- + O_2$$

To move a single electron down the chain requires the absorption of two photons. Therefore, to get four electrons (and yield one O_2 molecule), the photosynthetic apparatus needs to absorb eight photons of light, four by each photosystem.

Cyclic Electron Transport

Photosystem I can function independently of photosystem II in what is called cyclic electron transport (**Figure 6**). In cyclic electron transport, the electron transport from photosystem I to ferredoxin is not followed by electron donation to the $NADP^+$ reductase complex. Instead, reduced ferredoxin donates electrons back to plastoquinone. In this way, plastoquinone gets continually reduced and oxidized, and keeps moving protons across the thylakoid membrane without the involvement of photosystem II. The net result of cyclic electron transport is that the energy absorbed from light is converted into the chemical energy of ATP without the oxidation of water or the reduction of $NADP^+$ to NADPH. Cyclic electron transport is sometimes referred to as cyclic photophosphorylation, because the light energy captured in this cycle is ultimately used to drive the phosphorylation of ADP to ATP.

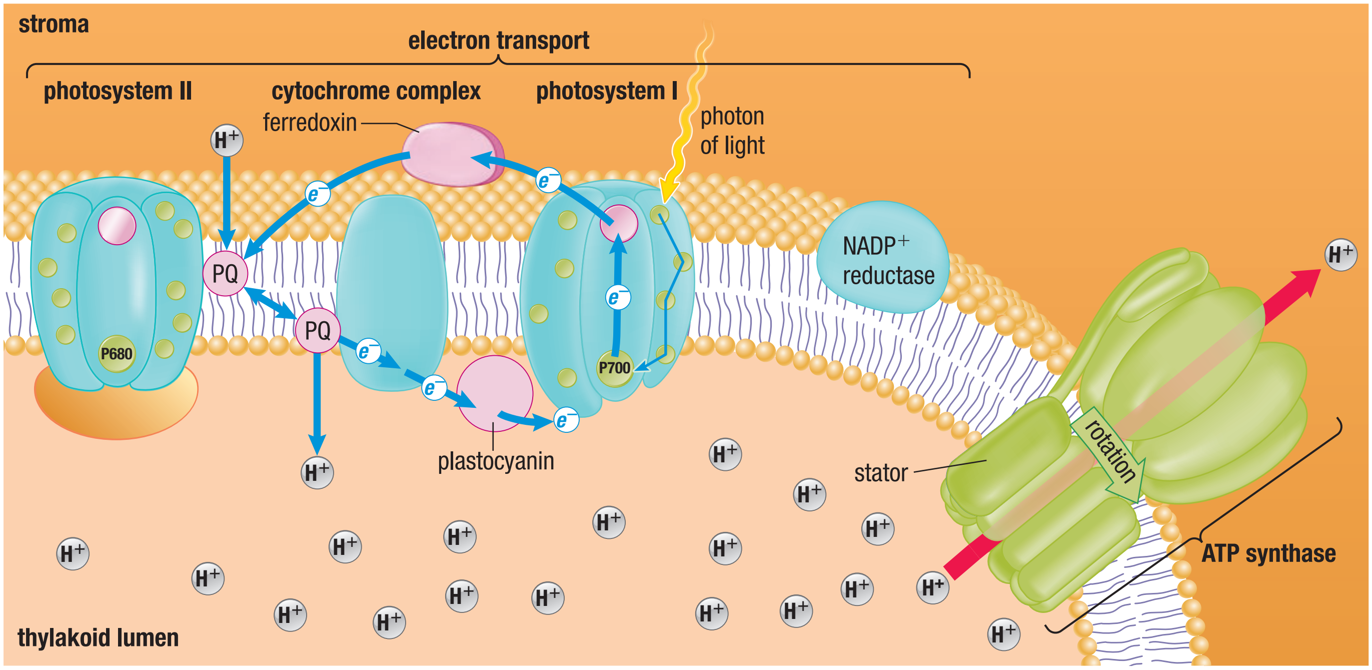


Figure 6 During cyclic electron transport, electrons move in a circular pathway from photosystem I, through ferredoxin to plastoquinone, through the cytochrome complex and plastocyanin, and then back to photosystem I. In cyclic electron transport, photosystem II does not operate. The pathway generates proton pumping, and thus leads to ATP production, but does not result in the synthesis of NADPH.

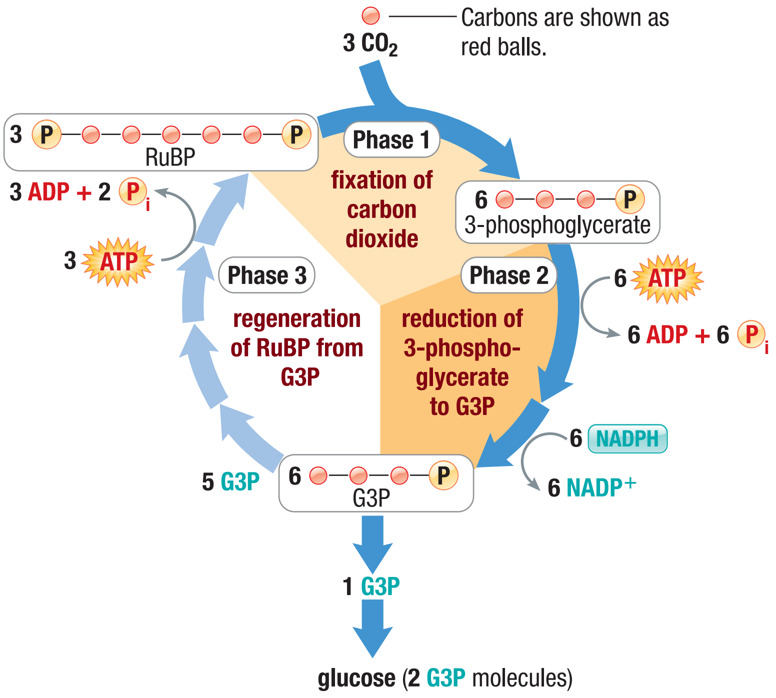
Cyclic electron transport plays an important role in overall photosynthesis. The reduction of carbon dioxide by the Calvin cycle requires more ATP than NADPH, and the additional ATP molecules are provided by cyclic electron transport. Other energy-requiring reactions in the chloroplast are also dependent on ATP produced by the cyclic pathway.

The Light-Independent Reactions

Recall, from the last chapter, that CO_2 is a fully oxidized carbon molecule and thus contains no usable energy. On the other hand, sugar molecules such as glucose and sucrose are highly reduced. They contain many C–H bonds and thus are an abundant source of energy. In the stroma of the chloroplast, a series of 11 reactions uses NADPH to reduce CO_2 into sugar. The overall process is endergonic, requiring energy supplied by the hydrolysis of ATP. These 11 enzyme-catalyzed (or light-independent) reactions are collectively known as the Calvin cycle. The Calvin cycle is by far the most dominant pathway on Earth by which CO_2 is fixed into carbohydrates. As you will learn in Section 5.4, many plants use a small number of additional light-independent steps immediately prior to the Calvin cycle.

How the Calvin Cycle Produces Carbohydrates

The Calvin cycle can be divided into three phases: fixation, reduction, and regeneration (**Figure 7**).



Carbons are shown as red balls.
3 CO_2
3 P—○—○—○—○—○—P RuBP
Phase 1
fixation of carbon dioxide
6 ○—○—○—P 3-phosphoglycerate
3 ADP + 2 P_i
3 ATP
Phase 3
regeneration of RuBP from G3P
Phase 2
reduction of 3-phosphoglycerate to G3P
6 ATP
6 ADP + 6 P_i
6 NADPH
6 $NADP^+$
5 G3P
6 ○—○—○—P G3P
1 G3P
glucose (2 G3P molecules)

Figure 7 The Calvin cycle reactions consist of three phases: carbon fixation (each CO_2 is incorporated into a 6-C compound), reduction (G3P is produced), and regeneration (RuBP is re-formed). The sum of three turns of the cycle (three CO_2 molecules) ultimately produces one molecule of a 3-carbon sugar, G3P, which can be used to make other organic molecules. The cycle also produces $NADP^+$, ADP, and P_i, which can then return to participate in the light-dependent reactions.

Phase 1: Carbon fixation. Carbon fixation is the conversion of carbon from an inorganic to an organic form. At the beginning of the Calvin cycle, CO_2, an inorganic compound, reacts with a molecule of ribulose-1,5-bisphosphate (RuBP), a 5-carbon sugar, to produce two 3-carbon molecules of 3-phosphoglycerate. This single step has monumental significance for life on Earth. Every carbon atom in every cell of virtually all living things has taken part in this chemical reaction. This type of photosynthesis is called a C_3 metabolism from the two 3-carbon molecules formed. In Section 5.4 you will learn about alternative mechanisms of photosynthesis.

Phase 2: Reduction. In Phase 2, each molecule of 3-phosphoglycerate gets an additional phosphate added from the hydrolysis of ATP. This molecule is subsequently reduced by high-energy electrons from NADPH, producing glyceraldehyde-3-phosphate (G3P).

Phase 3: Regeneration. In a multi-step process, some of the G3P molecules are combined and rearranged to regenerate the RuBP that is required to start the cycle over again.

In each complete Calvin cycle, one molecule of CO_2 is converted into one reduced carbon—essentially one CH_2O unit of carbohydrate. However, it takes three cycles to produce something the cell can actually use—one extra molecule of the 3-carbon sugar, G3P. To account for this, Figure 7 is a summary of three cycles, tracking the fate of three carbon atoms.

Examine Figure 7 again, keeping track of the carbons in each phase. In 3 complete turns of the cycle, 3 CO_2 (3 carbons) are combined with 3 molecules of RuBP (15 carbons), to produce 6 molecules of 3-phosphoglycerate (18 carbons). These go on to yield 6 molecules of G3P (totalling 18 carbons). Five of the 6 molecules of G3P (totalling 15 carbons) are used to regenerate the 3 RuBP molecules (15 carbons). Thus, the cycle generates 1 molecule of G3P (3 carbons) after 3 turns.

The production of this one molecule of G3P is the ultimate goal of photosynthesis. G3P is a high-energy carbon that contains raw material from which all other organic plant compounds are synthesized. For the synthesis of this one G3P, the Calvin cycle requires a total of nine molecules of ATP and six molecules of NADPH. The $NADP^+$, ADP, and P_i that are formed during the reduction phase, as well as the ADP and P_i formed during the regeneration phase, of the Calvin cycle, are regenerated to NADPH and ATP by the light reactions. These numbers must be doubled to 18 ATP and 12 NADPH for a single glucose molecule to be produced from two G3P.

RUBISCO: THE MOST ABUNDANT PROTEIN ON EARTH

Before concluding this overview of the Calvin cycle, turn your attention to a special chemical—the chemical that is responsible for the very first step in Phase 1 and the fixing of carbon. Ribulose-1,5-bisphosphate carboxylase oxygenase, or RuBisCO (commonly spelled **rubisco**), is the enzyme that catalyzes the first reaction of the Calvin cycle. It is arguably the most important enzyme of the biosphere. By catalyzing CO_2 fixation in all photoautotrophs, it provides the source of organic carbon molecules for most of the world's organisms. It begins the conversion of about 100 billion tonnes of CO_2 into carbohydrates annually. There are so many rubisco molecules in chloroplasts that the enzyme makes up 50 % or more of the total protein of plant leaves. As such, rubisco is also the world's most abundant protein, estimated to total some 40 million tonnes worldwide—equivalent to about 6 kg per person on Earth.

rubisco ribulose-1,5-bisphosphate carboxylase oxygenase; a critical enzyme that acts as a catalyst for the reduction of carbon dioxide in the Calvin cycle of photosynthesis

A Diversity of Organic Products

The G3P molecule formed by three turns of the Calvin cycle is the starting point for the production of a wide variety of organic molecules. Complex carbohydrates, such as glucose and other simple sugars (monosaccharides), are made from G3P by reactions that, in effect, reverse the first half of glycolysis. Once produced, the monosaccharides may enter biochemical pathways that make disaccharides such as sucrose, polysaccharides such as starches and cellulose, and other complex carbohydrates. Other biochemical pathways manufacture amino acids, fatty acids and lipids, and nucleic acids. The reactions that form these products occur both within chloroplasts and in the surrounding cytosol and nucleus.

Sucrose, a disaccharide that consists of glucose bonded to fructose, is the main form in which the products of photosynthesis circulate from cell to cell in higher plants. In most higher plants, organic nutrients are stored as sucrose, starch, or a combination of the two in proportions that depend on the plant species. Sugar cane and sugar beets, which contain stored sucrose in high concentrations, are the main sources of the sucrose you use as table sugar.

5.2 Review

Summary

- In the light-dependent reactions, photosystem II absorbs light energy that oxidizes the reaction centre chlorophyll P680, producing the powerful oxidant P680$^+$. This molecule oxidizes water, removing electrons and releasing O_2.
- Electrons that are excited by the light energy in photosystem II pass through an electron transport system to photosystem I. There, the electrons become excited again by the absorption of light and are ultimately transferred to NADP$^+$ as the final electron acceptor forming NADPH.
- These processes establish a proton gradient across the thylakoid membrane, which is then used to generate ATP through chemiosmosis.
- ATP synthase complexes in the thylakoid membrane harness the energy of the moving protons to produce ATP reactions that are identical to those seen in cellular respiration.
- In cyclic electron transport, electrons can also flow cyclically through photosystem I, further building up the H^+ concentration inside the thylakoid membrane and allowing extra ATP to be produced, but no NADPH.
- In the Calvin cycle, CO_2 is fixed and converted into reduced high-energy organic substances by the addition of electrons and protons that are carried by the NADPH produced in the light reactions. ATP, also derived from the light reactions, provides additional energy. Rubisco catalyzes the reaction that first fixes CO_2 into organic compounds.
- For every 3 complete turns of the Calvin cycle, a single molecule of the 3-carbon molecule G3P is produced. G3P is the starting point for the synthesis of glucose, sucrose, starches, and many other organic molecules.

Questions

1. Describe how a low-energy electron in water becomes a high-energy electron on the primary acceptor of a reaction centre. K/U
2. Sketch the linear electron transport chain that ends with the passing of final electrons to NADP$^+$ to create NADPH. K/U C
3. Why is light energy essential for photosynthesis to occur? K/U
4. Describe three steps that contribute to the buildup of the proton gradient across the thylakoid membrane. K/U
5. Why and how do protons move through the thylakoid membrane from the lumen to the stroma? K/U
6. Use a t-chart to compare the electron transport chains found in mitochondria and chloroplasts. K/U C
7. Consider the analogy of the cyclist (page 224). T/I C
   (a) Illustrate the analogy. Include labels for photosystem I, photosystem II, and ATP production.
   (b) Is the analogy a good one? Why or why not?
8. Careful measurements indicate that the Calvin cycle in a plant leaf is occurring very slowly. In such a situation, there is a reduced demand for both NADPH and ATP. T/I A
   (a) What benefit (if any) would the light-dependent reactions still have for this plant?
   (b) Can you think of any environmental conditions under which such a situation might arise?
9. Analysis of a plant's leaf showed an unusually high amount of ATP, but relatively little NADPH. Which electron transport method is probably working much more predominantly in this leaf? Which photosystem is probably absorbing more light energy? Explain your answer. T/I
10. Rubisco is the world's most abundant protein, yet it is not found inside any animal cells. Suggest a reason why animals do not need or use this protein. T/I A

The Calvin Cycle

ABSTRACT

Melvin Calvin used radioactive isotopes of carbon (^{14}C) and two-dimensional chromatography to identify the exact sequence of organic compounds created during photosynthesis. He replaced the carbon in the CO_2 made available to photosynthetic algae with ^{14}C. This allowed him to track the movement of carbon through the stages of photosynthesis. He studied these stages by exposing the algae to light for different periods of time and then quickly killing the algae. Then he extracted and separated out the organic compounds in the algae by chromatography. He then produced chromatograms using photographic film that showed which chemical compounds contained ^{14}C each time. This allowed him to detail the exact steps that occur when photosynthesis transforms CO_2 into complex organic molecules.

Introduction

Despite its importance to the existence of life on Earth, photosynthesis has only become understood relatively recently. In the 1940s, Melvin Calvin at the University of California at Berkeley devised an ingenious method for tracking the movement of carbon through the carbon-reducing cycle of photosynthesis. It would eventually be named in his honour. Calvin described the key elements of his experimental design in the introduction to his 1948 paper:

> *The ideal design of an experiment to determine the chemical path of carbon from carbon dioxide to the variety of plant constituents is relatively simple and straightforward. It would consist of feeding a photosynthesizing organism radioactive carbon dioxide for various lengths of time and stopping the reaction by killing the plant.*

Methods

The chemical reactions of photosynthesis occur so rapidly that they are not easy to study. Calvin had to develop a method that would separate the photosynthesis reactions from other reactions in the plant, isolate the stages of photosynthesis, and track the movement of carbon through these stages. Calvin's great innovation was his ability to track carbon atoms through the reaction pathway by using a radioactive isotope of carbon, ^{14}C. Calvin (1948) explained the idea of using radioactive carbon in his third of a series of many papers related to photosynthesis:

> *The availability of isotopic carbon, that is, a method of labeling the carbon dioxide, provides the possibility of some very direct experiments designed to recognize these intermediates and, perhaps, help to understand the complex sequence and interplay of reactions, which must constitute the photochemical process itself.*

The ^{14}C isotope behaves in an identical way chemically to that of ^{12}C, but it emits very small amounts of radiation. By exposing the algae to carbon dioxide containing the ^{14}C isotope, any uptake of carbon atoms during photosynthesis would be radioactive and could be detected.

Using the radioisotope of carbon allowed Calvin to determine the various compounds formed from the carbon that is fixed during photosynthesis. However, Calvin also wanted to determine the sequence of photosynthetic reactions—the precise order in which these compounds were formed in a chemical pathway.

For his experiment, Calvin chose a simple unicellular algae, *Chlorella*, in which each cell contained only one chloroplast. He spread out a suspension of these cells in a thin layer inside a flat glass container (**Figure 1**). Calvin kept the *Chlorella* in the dark with a supply of $^{14}CO_2$, knowing that the instant he turned on the light they would begin photosynthesis and uptake $^{14}CO_2$. For each trial, he exposed the cells in the reaction vessel to light for a brief time interval ranging from a few seconds to 30 s. To stop each trial at the predetermined time, he killed the algae instantly by plunging them into boiling alcohol.

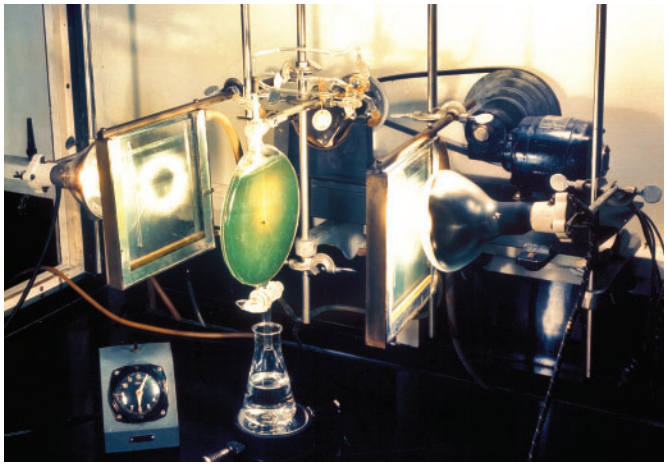


Figure 1 Calvin's "lollipop" apparatus

Next, Calvin extracted the organic compounds from the dead algae cells from each trial and separated them by two-dimensional chromatography. This process uses two different solvents to physically separate different compounds across an entire surface. In this process, Calvin put a drop of the extract from the algae in the corner of a piece of filter paper and then placed the filter paper in a solvent. This separated out various chemicals from the algae extract as the solvent moved up the paper. Then Calvin rotated the paper 90° and placed it in a different solvent to separate those same chemicals in the other direction.

Calvin then identified the compounds that contained ^{14}C by placing the chromatograms on a sheet of photographic film where the radioactive carbon left dark spots on the developed film. Calvin used the sequence of chromatogram images to track the formation of new ^{14}C-containing compounds over time—he determined which compounds were formed and in what order.

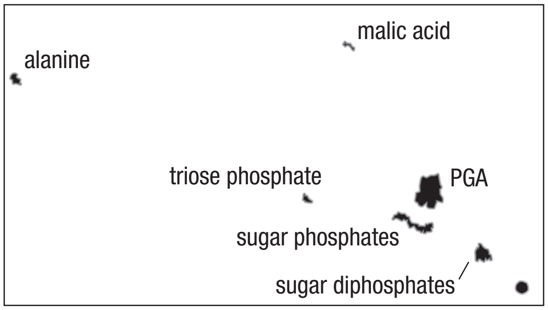
Observations

Interpreting the chromatogram evidence was challenging, as the reactions took place in very rapid sequence (**Figure 2**). By comparing the chromatogram images from each trial and considering a variety of factors, Calvin eventually determined the steps in the cycle.

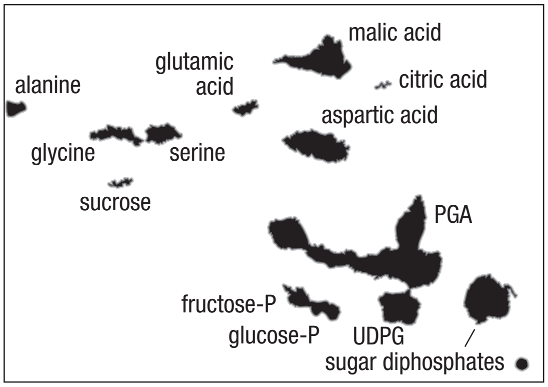
Discussion

The processes and products described in Calvin's first paper were the first of many experiments dealing with the cyclic pathway of the generation of carbohydrates. Between 1948 and 1953, Calvin and his team published 21 papers describing their research on the cyclic pathway of photosynthesis. Each resulted from their insightful use of radioisotopes and their creative experimental design, which permitted them to stop the reaction pathway after specific time intervals.

Calvin's findings and the ingenuity of his approach allowed fast advances, not only in the field of photosynthesis but also in many other biochemical studies. He was awarded the 1961 Nobel Prize in Chemistry for his research. It had been almost 60 years since the 1902 Nobel Prize winner, Emil Fischer, was rewarded for his research on the structure of glucose—the end product of the Calvin cycle.



(a) pattern after 5 s of photosynthesis with *Chlorella* in $^{14}CO_2$



(b) pattern after 30 s of photosynthesis with *Chlorella* in $^{14}CO_2$

Figure 2 Chromatogram patterns obtained after (a) 5 s and (b) 30 s of photosynthesis. The variety of organic compounds is an indication of the speed and complexity of these biochemical pathways.

Citations and Further Reading

Calvin, M., & Benson, A.A. (1948). *The Path of Carbon in Photosynthesis.* Berkeley, California: Ernest Orlando Lawrence Berkeley National Laboratory, University of California Radiation Laboratory.

Calvin, M. (1992). *Following the trail of light: A scientific odyssey.* Washington, D.C.: American Chemical Society.

Melvin Calvin's biography on the Encyclopedia Britannica website.

WEB LINK

5.3 Questions

1. What problem did Calvin set out to solve? K/U
2. Briefly explain the approach that Calvin used to solve the problem. Why was this process innovative? K/U
3. Imagine that one of Calvin's chromatograms was found to contain radioactive G3P but no radioactive RuBP. What other radioactive compound(s) would you expect to find on the same chromatogram? Refer to Figure 7 on page 226 to answer this question. T/I
4. How did the use of radioisotopes and chromatography allow Calvin to track where the carbon dioxide taken in by the algae had gone? T/I
5. Calvin collaborated with other scientists. Research with whom he worked and write brief biographies about those scientists. T/I C

WEB LINK

Alternative Mechanisms of Carbon Fixation

In addition to light, plants need the raw materials for photosynthesis: carbon dioxide and water. Atmospheric carbon dioxide is available to every land plant and to aquatic plants whose leaves float on the surface of the water. For submerged aquatic plants, carbon dioxide is available in the form of dissolved carbonic acid. Carbon dioxide, however, makes up only 0.04 % of the atmosphere—a concentration $\frac{1}{500}$ that of the oxygen gas we breathe! This ratio has significant consequences for photosynthesis.

Preventing Water Loss

Water is the major component of the cytosol and is therefore always available for photosynthesis; however, all land plants have adaptations to limit water loss and respond to changes in water availability. These adaptations can reduce a plant's ability to exchange gases with its environment. Perhaps the most important adaptation for plants on land is the presence of a waxy cuticle. This thin waterproof layer covers the top and bottom surface of all terrestrial plant leaves. It seals off the interior of a leaf from the outside environment and prevents what would otherwise be a rapid loss of water by evaporation. To enable controlled gas exchange with the atmosphere, each leaf has many microscopic **stomata** (singular: stoma)—small pores on the leaf's surface that can be opened and closed by the surrounding pair of guard cells (**Figure 1**). The stomata open during the day, allowing carbon dioxide to enter and be used for photosynthesis. When the stomata are open, some water is lost through transpiration (loss of water vapour through stomata), but this water is replaced by water taken up by the plant's roots. At night, photosynthesis stops and the stomata close to conserve water. When a plant is at risk of losing too much water due to high temperatures or there is a shortage of water in the soil, the stomata remain closed even during the day.

stomata small pores in the surface of a leaf that can be opened and closed to control the exchange of gases between the atmosphere and the leaf interior

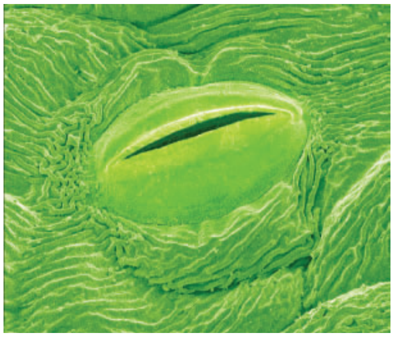


Figure 1 Gas exchange and water loss by a plant are controlled by the presence of stomata. Each stoma is formed from two guard cells.

Photorespiration: The Problem with Rubisco

All biological reactions are catalyzed by enzymes. As you have learned, the rate and efficiency with which enzymes function is influenced by many factors, including temperature, pH, and the presence of inhibitors. During photosynthesis, the functioning of the single most abundant enzyme on Earth can be problematic.

Rubisco is a very slow enzyme, catalyzing the fixation of only about three molecules of CO_2 per second. Its slow rate of catalysis is countered by its abundance within the cells. In addition to being slow, rubisco's active site occasionally binds with oxygen gas instead of carbon dioxide and catalyzes a reaction between a molecule of O_2 and RuBP. This ability to catalyze a reaction involving either CO_2 or O_2 is why rubisco is called ribulose-1,5-bisphosphate *carboxylase oxygenase*. One of the products of the reaction between O_2 and RuBP is a molecule that is not useful to the cell. This molecule must be converted back into a useful molecule to prevent too much RuBP from being wasted. The recovery pathway is long and involves reactions within the chloroplast, peroxisomes, and mitochondria. It consumes ATP and releases a molecule of CO_2. This means that, instead of fixing CO_2, the oxygenase activity of rubisco does the opposite. Since O_2 is a reactant in the recovery pathway and CO_2 is produced at later steps, the entire process is termed **photorespiration**.

photorespiration the catalysis of O_2 instead of CO_2 by rubisco into RuBP, which slows the Calvin cycle, consumes ATP, and results in a release of carbon

Under laboratory conditions, when concentrations of both O_2 and CO_2 are equal, the binding of CO_2 will happen more frequently because the active site of rubisco has a greater attraction for CO_2 than for O_2. In fact, the binding with CO_2 will occur about 80 times as fast as the binding with O_2. In nature, however, the atmosphere does not contain equal amounts of the two gases—it contains about 21 % O_2 and about 0.04 % CO_2. Since the amount of O_2 in the atmosphere is so much greater than the amount of CO_2, under normal atmospheric concentrations and at moderate temperatures rubisco will bind with CO_2 about 75 % of the time. This means that 25 % of the time, rubisco binds with O_2 and releases rather than fixes a molecule of CO_2. This is a drain on cell resources, but the plant can still fix enough carbon to meet its normal demands for the production of energy-rich carbohydrates. However, if the supply of CO_2 in the cell is significantly reduced, photorespiration becomes a much more serious concern.

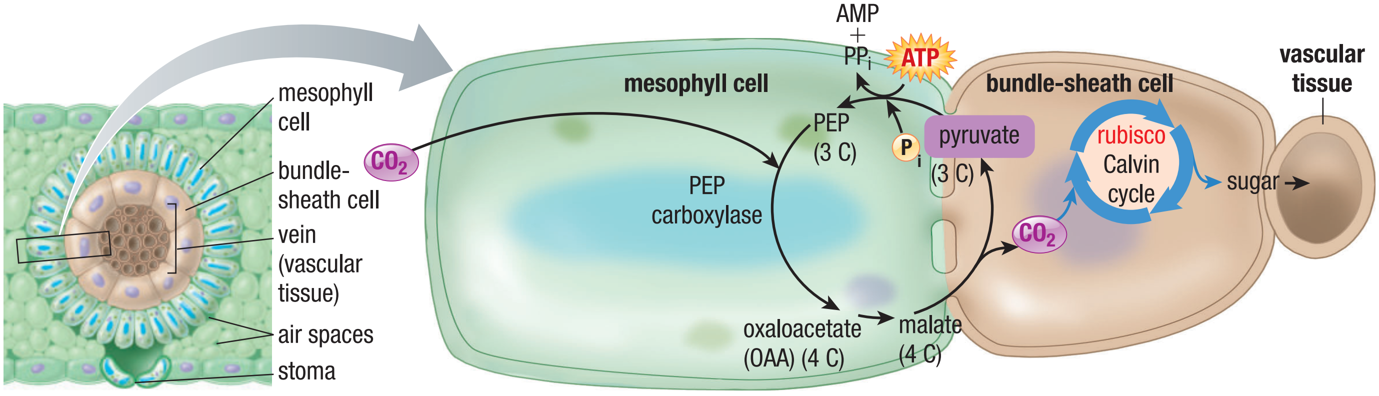
Many terrestrial plants, especially those living in hot, dry climates, face the problems of photorespiration and water loss (**Figure 2**). They need to open their stomata to let in CO_2 for the Calvin cycle, but they need to keep the stomata closed to conserve water. When stomata are closed, or even partly closed, less CO_2 can enter the leaf, and, as the CO_2 that is present is consumed in the Calvin cycle, its concentration drops and photorespiration increases. This dilemma is even worse in warm climates because the solubility of O_2 and CO_2 decreases as the temperature increases. (The stroma, where the Calvin cycle occurs, is an aqueous environment.) The solubility of CO_2 decreases more rapidly than that of O_2 as the temperature increases, resulting in a decrease in the $CO_2:O_2$ ratio. As this ratio decreases, photorespiration increases. In high temperatures, as much as 50 % of the plant's energy could be wasted by photorespiration.

Figure 2 Plants living in hot, dry environments struggle to exchange gases with the atmosphere without suffering excessive water loss. These plants have evolved a variety of adaptations in response to the harsh conditions.

C_4 Plants

Some plant species found in hot, dry climates have an internal leaf structure and mode of carbon fixation that minimizes photorespiration. In these plants, the reactions of the Calvin cycle are performed by bundle-sheath cells, which surround the leaf veins (**Figure 3(a)**). Bundle-sheath cells are surrounded by mesophyll cells that separate them from the air spaces within the leaf. This separation reduces the exposure of the rubisco-containing bundle-sheath cells to oxygen gas and therefore reduces the rate of photorespiration. The mesophyll cells also reduce access to CO_2, but this is not a problem because they operate a second carbon fixation pathway called the **C_4 cycle.** In the C_4 cycle, CO_2 combines with a 3-carbon molecule, phosphoenolpyruvate (PEP), to produce the 4-carbon oxaloacetate. Oxaloacetate is then reduced to malate by electrons transferred from NADPH. The malate diffuses into the bundle-sheath cells, where it enters chloroplasts and is oxidized to pyruvate, releasing CO_2 (**Figure 3(b)**). The combined effect of the physical arrangement of cells and the C_4 pathway establishes a high concentration of CO_2 around the rubisco while reducing its exposure to oxygen.

C_4 cycle an alternative form of carbon fixation that some plants use, particularly in hot weather, to increase the concentration of CO_2 available for the Calvin cycle reactions



(a) C_4 leaf anatomy

(b) C_4 pathway

Figure 3 The C_4 cycle

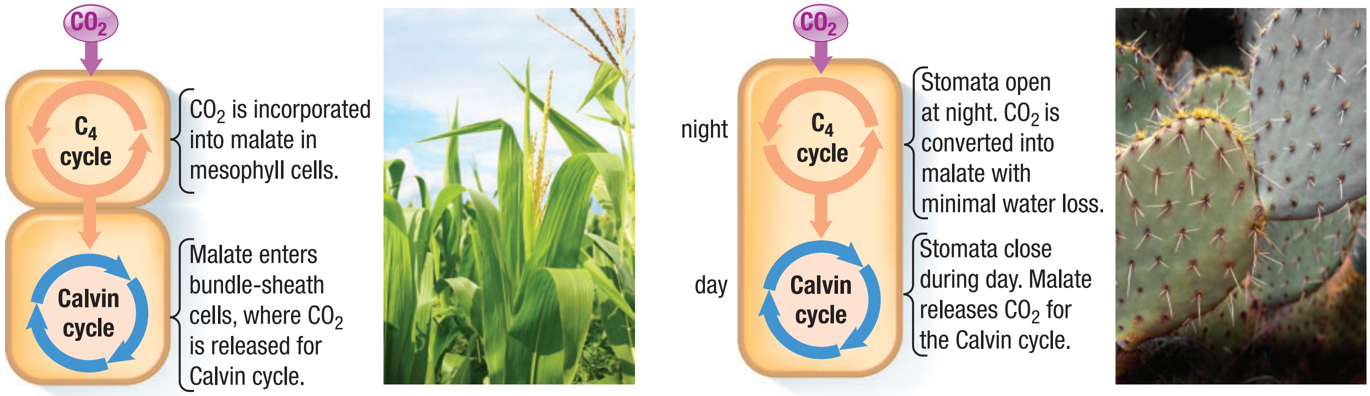
A key distinction between C_4 and C_3 metabolism is related to the binding of CO_2. In the C_4 cycle, the initial binding of CO_2, which incorporates CO_2 into phosphoenolpyruvate, is catalyzed by the enzyme PEP carboxylase. Unlike rubisco, PEP carboxylase has a much greater affinity for CO_2 than for O_2, so it can efficiently catalyze the binding of PEP regardless of the O_2 concentration near the enzyme. Many tropical plants and several temperate crop species, including corn and sugar cane, have C_4 metabolism. Remember that C_4 plants use the Calvin cycle as well.

Even though C_4 metabolism helps prevent photorespiration, it is not widespread among plants. For each turn of the C_4 cycle, the double hydrolysis of ATP to AMP (adenosine monophosphate) is required to regenerate PEP from pyruvate. This means that there is an additional energy requirement, equivalent to six ATP for each G3P produced by the Calvin cycle. However, in hot climates, photorespiration can decrease carbon fixation efficiency by over 50 %, so the C_4 pathway is worth the energy cost. Hot climates also tend to receive a lot of sunshine, so the additional ATP requirement is easily met by the cyclic light reactions. This enhanced efficiency has a number of implications. C_4 plants can open their stomata less than C_3 plants, enabling them to survive better in arid environments. C_4 plants also require one-third to one-sixth as much rubisco, and so have a much lower nitrogen demand. This enables them to survive in more nutrient-poor soil conditions. In temperate climates, the lower temperatures mean that photorespiration is less of a problem, and the additional ATP requirement is harder to meet with less sunshine. In Florida, for example, 70 % of native species are C_4 plants, but there are no C_4 species in Manitoba. CAREER LINK

CAM Plants

The C_4 plants run their Calvin and C_4 cycles simultaneously but in different locations (**Figure 4(a)**). Other plants run their Calvin cycle and C_4 cycle in the same cells, but do so at different times of the day (**Figure 4(b)**). These plants are known as **CAM** (**crassulacean acid metabolism**) plants. The name is derived from the Crassulaceae family in which the metabolic pathway was first observed, and from the plants' night-time accumulation of malic acid.

crassulacean acid metabolism (CAM) a metabolic pathway, used mostly by succulent plants, in which the Calvin cycle and the C_4 cycle are separated in time for better efficiency of CO_2 fixation


CO2
C4 cycle
Calvin cycle
CO2 is incorporated into malate in mesophyll cells.
Malate enters bundle-sheath cells, where CO2 is released for Calvin cycle.
CO2
night
day
C4 cycle
Calvin cycle
Stomata open at night. CO2 is converted into malate with minimal water loss.
Stomata close during day. Malate releases CO2 for the Calvin cycle.

(a) plants controlling location of C_4 cycle

(b) plants controlling time of C_4 cycle (CAM)

Figure 4 (a) Some C_4 plants, such as corn, control the location of the C_4 and Calvin cycles. (b) CAM plants, such as beavertail cactus (*Opuntia basilaris*), also use a C_4 cycle, carrying out the two cycles in the same cells but at different times.

CAM plants typically live in regions that are hot and dry during the day and cool at night. These cacti and succulent species, with fleshy leaves or stems, have a low surface-to-volume ratio, and fewer stomata. Furthermore, their stomata open only at night, when they release the O_2 that accumulates from photosynthesis during the day and allow CO_2 to enter. The CO_2 that enters is fixed by a C_4 pathway into malate, which accumulates throughout the night and is stored in the form of malic acid in cell vacuoles. Daylight initiates the second phase of the CAM process. As the Sun rises and the temperature increases, the stomata close, reducing water loss and cutting off the exchange of gases with the atmosphere. Malic acid diffuses from cell vacuoles into the cytosol, where the malate is oxidized to pyruvate, and a high concentration of CO_2 is released. The high concentration of CO_2 favours the carboxylase activity of rubisco, allowing the Calvin cycle to proceed efficiently with little loss of CO_2 from photorespiration. The pyruvate produced by malate breakdown accumulates during the day, but is converted back to malate during the night. As in other C_4 plants, this step requires an expenditure of ATP. CAREER LINK

UNIT TASK **BOOKMARK**

You can use what you have learned about photosynthesis and climate to design your Unit Task investigation on page 252.

5.4 Review

Summary

- O_2 can compete with CO_2 for the active site of the enzyme rubisco, reducing the efficiency of photosynthesis. The resulting pathway is called photorespiration.
- Some plants have evolved a C_4 pathway as well as a physical arrangement and specialization of cells that bypass the problems of photorespiration. They do this by incorporating CO_2 into a 4-carbon compound in mesophyll cells and then transporting it to bundle-sheath cells.
- C_4 plants are significantly more efficient than C_3 plants at performing photosynthesis in hot and/or dry environments.
- Many cacti and succulent plants use crassulacean acid metabolism (CAM), which uses a C_4 cycle to fix carbon during the night and the Calvin cycle to produce carbohydrates during the day.

Questions

1. Explain why plants sometimes have difficulty getting all the CO_2 they need to photosynthesize efficiently. K/U
2. Wheat, corn, and rice are all grasses, and all are extremely important food crops for humans and livestock. Based on what you know about these plants, predict whether they are C_3, C_4, or CAM plants. Go online and conduct research to find out if your predictions were correct. T/I
3. Why does PEP carboxylase do a better job than rubisco at fixing CO_2 in plants that use the C_4 pathway? In what type of environment is PEP carboxylase more effective than rubisco? K/U
4. You and a friend are observing a field of lush green grass on a hot, sunny summer day. Your friend suggests that the grass must be growing quickly that day. Why might this not be the case? T/I
5. Which type of plant (C_3, C_4, or CAM) would you expect to grow most efficiently in each environment? Explain your reasoning. K/U T/I
   (a) a hot, wet tropical environment
   (b) an environment with extremely hot days but cool nights
   (c) a cool, damp environment
   (d) an environment with a moderate climate but nutrient-poor soil
6. Working with a partner, brainstorm a list of 10 different plant species. Do online research to determine, for as many of these plants as you can, what type of carbon fixation strategy they use. T/I
7. A student takes a variety of small houseplants and surrounds each plant with a clear plastic bag. After a few hours, the student observes that water vapour has condensed on the inside of some of the bags. T/I
   (a) Do you think such an experiment would provide any evidence of the type of carbon fixation strategy used by each plant? Explain your reasoning.
   (b) Would you expect different results if the student had conducted the experiment during the day versus during the night?
8. Suggest one or more reasons why scientists are interested in genetically modifying plants to change their carbon fixation pathways. T/I A
9. Which carbon fixation pathway would you expect an aloe vera plant (**Figure 5**) to use? Explain why. T/I

Figure 5 Aloe vera plant

WEB LINK

5.5 Explore Applications in Artificial Photosynthesis

Can Artificial Photosystems Produce Fuel?

SKILLS MENU

- Researching
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating
- Identifying Alternatives

In March of 2011, scientists from the Massachusetts Institute of Technology announced the development of the first practical "artificial leaf." The device is about the size of a playing card. When it is placed in water and exposed to sunlight, it is able to generate electricity using a process that begins by splitting water into hydrogen and oxygen gas (**Figure 1**). The research teams' stated goal is to enable homes to generate their own power. CAREER LINK

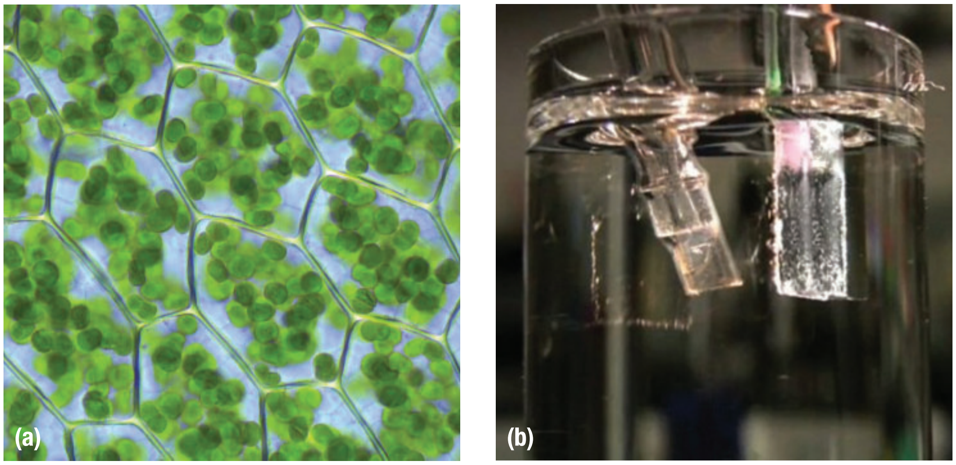


Figure 1 (a) Could the power of photosynthesis in chloroplasts like these (b) be harnessed as a future energy source?

Although plants and other producers convert solar energy into more than enough energy to sustain life on Earth, humans never seem to have enough energy. We harness hydro and nuclear power, mine for coal, drill for oil, process tar sands, and extract natural gas from beneath Earth's surface to meet our energy needs. Each of these methods has significant impacts on the environment and our economy. Disasters such as the meltdowns that occurred at the Fukushima nuclear generating station in Japan in 2011, as well as the growing concern about climate change, highlight the severity of the impact of our methods of energy production. Increasingly, there is a desire to develop technologies that produce "green" energy that can be generated endlessly with minimal harm to the environment.

The Application

In pursuit of this goal, people have begun to question why we do not simply follow the lead of photosynthetic organisms. Although solar panels allow us to collect and transform some light energy into electricity, what if we could transform light energy into fuel? Scientists are working to copy the energy-trapping power of photosynthesis itself. Unlike plants, which use sunlight to synthesize sugars and other complex organic molecules, scientists are hoping to use the energy-capturing ability of photosystems more directly. As you have learned, photosystem II is able to split water molecules, separating the hydrogen electrons and protons from oxygen atoms. If, for example, the free energized electrons or hydrogen gas could be captured using artificial photosystems, they could be used to generate electricity or to provide a high-energy, clean-burning fuel. In this activity, you will conduct research to learn how scientists are working to develop practical and innovative green energy technologies that mimic the actions of natural photosystems.

Your Goal

Your goal is to assess the current status of artificial photosystem technology. You will take on the role of a science adviser whose task is to prepare a report or presentation for a government panel. Your report will describe the science and technology of artificial photosystems.

Before beginning your research, decide what format you would like to use to present your findings and obtain approval from your teacher. You may be given the option of presenting your findings in an oral, written, or visual format.

Research

Conduct online research about the current scientific work being done to develop artificial photosystems. Use your research findings to answer the following questions:

- How does this technology harness energy through artificial photosynthesis?
- Why does this technology seem to hold so much promise?
- In which ways is this technology considered "green" compared to other ways of producing energy? In what ways is it less "green"?
- How efficient is the process of photosynthesis in plants and other organisms? How efficient is the new technology being developed?
- What are some of the limitations faced by scientists who are working on this new technology?
- Are scientists optimistic about this technology? Are you optimistic after researching it?
- What benefits might this technology provide to society and the environment? What are the risks of this technology? WEB LINK

UNIT TASK **BOOKMARK**

What information about the production of fuel using artificial photosynthesis could you use in your Unit Task on page 252?

Summarize

As you conduct your research, organize and then summarize your findings under appropriate headings (for example, the science behind the technology, the advantages and potential benefits of the technology, the challenges and potential drawbacks of the technology). This will assist you in preparing your report.

Communicate

Once you have summarized your findings, you are ready to communicate them. You will be asked to present your findings in an oral, written, or visual report. If time permits, you may be able to participate in a class discussion or conduct a role-play activity in which different students take on the role of an adviser or a member of a government panel.

WEB LINK

Photosynthesis and Cellular Respiration: A Comparison

5.6

Aerobic cellular respiration and photosynthesis are the two main chemical processes that are essential to most of the life on Earth. They fit together like pieces of a puzzle, completing a cycle of energy transformation in living things. This cycle occurs both at the cellular level and on the scale of entire ecosystems. As you learned in this chapter, photosynthesis converts sunlight into chemical energy for use as food by the organisms themselves and by organisms at higher trophic levels. Photosynthesis occurs in the cells of autotrophs such as plants, algae, and cyanobacteria. As you learned in Chapter 4, aerobic cellular respiration is used by the vast majority of eukaryotic and many prokaryotic heterotrophs, and by all photosynthesizing organisms. Aerobic cellular respiration extracts chemical energy from food and converts it into chemical potential energy within ATP. This potential energy of ATP then supplies the free energy that is needed to drive all other cellular metabolic activities.

In eukaryotes, photosynthesis occurs in the chloroplast, while aerobic cellular respiration begins in the cytosol and is completed within the mitochondrion. These processes are complementary (**Figure 1**). Photosynthesis produces oxygen and sugars, which are the reactants for cellular respiration. In turn, the waste products of cellular respiration—water and carbon dioxide—are the reactants for photosynthesis.

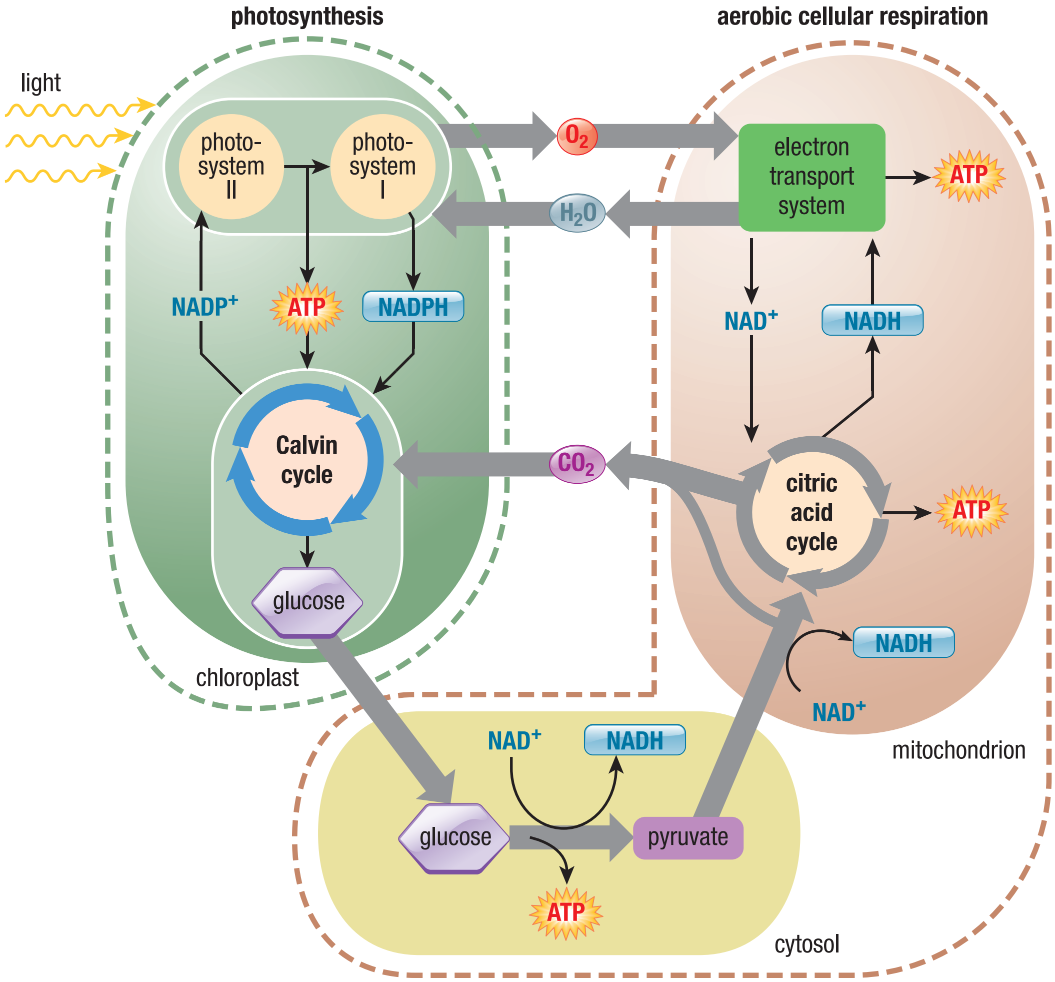
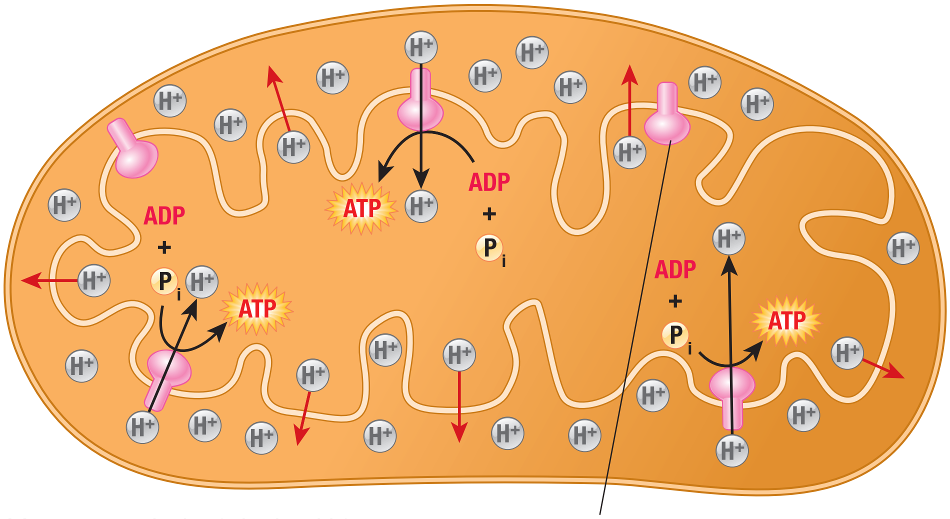


Figure 1 Photosynthesis (outlined in green) and aerobic cellular respiration (outlined in brown) are complementary—they use each other's products. The NAD^+ that are reduced to NADH in the cytosol and during pyruvate oxidation are also regenerated by the transfer of their hydrogens and high-energy electrons to the electron transport chain. For simplicity, H^+, ADP, and P_i are not shown in this diagram.

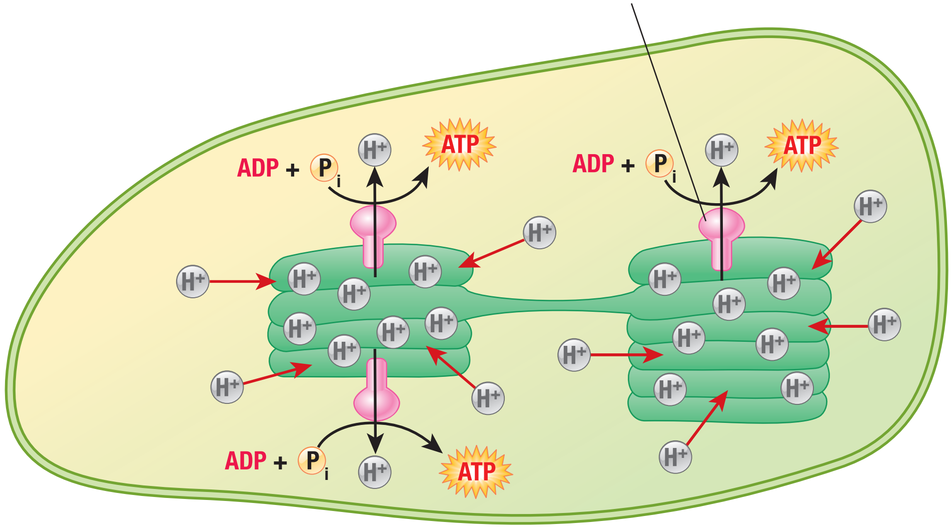
Chemical Steps and Reaction Processes

In addition to being complementary, photosynthesis and aerobic cellular respiration share many similar chemical steps and processes. Both reactions use electron transfer chains, along with ATP synthase complexes, to generate ATP by chemiosmosis. Both also use and regenerate carrier molecules. In photosynthesis, $NADP^+$ molecules are reduced during the light-dependent reactions to NADPH molecules, which then deliver hydrogens and their high-energy electrons to the Calvin cycle for use in carbohydrate synthesis. In aerobic cellular respiration, molecules of both NAD^+ and FAD (not shown in Figure 1) are used to carry hydrogens and their high-energy electrons to an electron transport chain. There, they are oxidized using oxygen to produce water and generate ATP.

Even the key organelles that are involved in each reaction share structural features. The chloroplasts used in photosynthesis and mitochondria used in cellular respiration have inner folded membranes that create separated fluid-filled spaces that allow proton gradients to be established (**Figure 2**). Both have complementary carbon-fixing (Calvin) and carbon-releasing (citric acid) cycles. Chloroplasts and mitochondria even possess their own unique DNA and replicate independently of cell division.



(a) cellular respiration (mitochondria)



(b) photosynthesis (chloroplasts)

Figure 2 Comparison of chemiosmosis in mitochondria and in chloroplasts. (a) In mitochondria, the proton gradient is established by pumping hydrogens out of an internal space (the matrix). (b) In chloroplasts, the proton gradient is established by pumping hydrogens into an internal space (the thylakoid lumens).

Comparison of Animals and Plants

Although we associate plant cells with photosynthesis, we know that photosynthesis requires the presence of the green pigment chlorophyll. Most plant cells, however, are not green and, like animal cells, are incapable of performing photosynthesis. These non-green cells form the roots, inner parts of stems, and various reproductive parts of a plant (**Figure 3**). All green plants contain at least some chlorophyll-bearing cells, typically within the leaves and green stems. These cells perform photosynthesis, producing energy-rich food molecules to be distributed throughout the plant. Herbivores then eat the plant, passing on the energy from photosynthesis. In this way, life is sustained at higher and higher trophic levels. Within chloroplasts, therefore, light's energy really does become life's energy.

All growing plant and animal cells require a non-stop supply of energy in the form of energy-rich ATP. They also require a supply of organic building materials, which they use to construct membranes, fibres and filaments, flagella and cilia, chromosomes, and all other cellular structures (**Table 1**). To meet these needs, organisms consume food for use both as a fuel and as raw building materials. When the food is used as a fuel, it enters the aerobic respiration pathway. When the food is used as building materials, the food molecules are disassembled and enter a variety of different metabolic pathways. Of these pathways, protein synthesis is particularly significant. In the next unit, you will examine the relationship between the genetic information you inherit from your parents and the control of protein synthesis.

Figure 3 While we think of most plants as being green, only certain cells of the above-ground structures are actually green.

Table 1 Comparison of Plant and Animal Demands for Energy and Materials

	Plants	Animals
Primary energy source	light	food
Method of obtaining primary energy source	photosynthesis	consumption of other living organisms
Energy storage	carbohydrates and other energy-rich molecules, such as fats and lipids	
Immediate source of free energy	ATP	
Primary source of ATP	aerobic cellular respiration	
Primary organic materials for growth, reproduction, and repair	carbohydrates, lipids, proteins, and nucleic acids	
Source of carbon in organic materials	carbon fixation during photosynthesis	consumption of other living organisms

5.6 Review

Summary

- Aerobic cellular respiration and photosynthesis create a cycle. Some of the products of one process serve as the reactants for the other process, and vice versa.
- Photosynthesis occurs in the chloroplasts of cells, while part of aerobic cellular respiration occurs in the mitochondria.
- The chemical processes and physical structures that are associated with photosynthesis and aerobic cellular respiration have many similarities.
- Plants and most other producers perform both photosynthesis and aerobic cellular respiration.
- Most consumers perform aerobic cellular respiration; however, they must rely on producers for the synthesis of the organic molecules they use as energy and as building materials for growth.

Questions

1. Which organelles are the sites of photosynthesis in eukaryotes? Do all plant cells contain these organelles? K/U
2. Which organelles are the sites of the oxygen-requiring stages of aerobic cellular respiration in eukaryotes? Do all plant and animal cells contain these organelles? K/U
3. The following equation is aerobic cellular respiration from left to right and photosynthesis from right to left. K/U T/I A

   $C_6H_{12}O_6 + 6O_2 \leftrightarrow 6\ CO_2 + 6\ H_2O$

   (a) Explain why this equation is misleading about the complexity of the interrelationship of photosynthesis and respiration.

   (b) Describe why the photosynthesis respiration equation is easily understood in terms of heterotrophs but often leads to misconceptions about energy use in plants.

   (c) From the photosynthesis and respiration equation, many people think that O_2 is created from CO_2. What does the CO_2 actually get converted to, and what does the O_2 in respiration become?
4. Compare the structure and function of chloroplasts and mitochondria. Do all the reactions of photosynthesis take place in the chloroplasts? Do all the reactions of aerobic cellular respiration take place in the mitochondria? K/U T/I
5. Make a Venn diagram to compare photosynthesis and aerobic cellular respiration. Consider their location within the cell, their primary energy source, and their reactants and products. T/I C
6. What is the relationship between autotrophs and heterotrophs in terms of photosynthesis and aerobic respiration? T/I
7. Compare and contrast the electron transport chains in photosynthesis with electron transport in cellular respiration. T/I
8. Contrast the source of electrons for aerobic cellular respiration and photosynthesis. K/U
9. Describe the roles of NADPH and NADH in the processes of photosynthesis and aerobic cellular respiration. T/I
10. Use Figure 1 (page 237) to explain the pathway of a carbon atom, beginning in a molecule of carbon dioxide, as it undergoes photosynthesis and then aerobic cellular respiration. T/I C
11. Both chloroplasts and mitochondria carry their own DNA. Do online research to find out the function of this DNA. How is the DNA in your own mitochondria inherited? Do you have a mix of your father's and mother's mitochondrial DNA? T/I A

WEB LINK

CHAPTER 5 Investigations

Investigation 5.1.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Light and Photosynthesis

The process of photosynthesis converts light energy into chemical energy, which is stored in the form of simple sugars or starch. In this investigation, you will test the influence of light on a plant's ability to produce starch.

Testable Question

Does the presence or absence of light affect the amount of starch that can be produced through photosynthesis?

Hypothesis

Formulate a hypothesis based on the influence of light on a plant's ability to produce starch.

Variables

What are the dependent and independent variables in this experiment? What variables may need to be controlled?

Experimental Design

You will use plant leaves to investigate the effects of light conditions (light/no light) on starch synthesis. You will manipulate a leaf so that one area of the leaf is exposed to light while another area is kept in the dark. After a period of exposure to light, you will test for the presence of starch in the illuminated and non-illuminated portions of the leaf.

Equipment and Materials

SKILLS HANDBOOK A1.2

- scissors
- paper clips
- light source
- chemical splash-proof safety goggles
- lab apron
- 250 mL beaker
- hot plate
- utility stand
- ring clamp
- 20 mm × 200 mm test tube
- test-tube rack
- glass stirring rod
- test-tube holder
- forceps
- Petri dish
- 2 pieces of opaque black paper, 5 cm × 5 cm
- plant that has been kept in the dark for 48 h
- 95 % ethanol (denatured) or 70 % isopropyl alcohol
- Lugol's iodine solution in a dropper bottle

Do not touch the top of the hot plate. When unplugging the hot plate, pull on the plug, not the cord. A Bunsen burner cannot be used because ethanol vapour is flammable.

Ethanol is flammable and toxic.

Lugol's iodine solution is an irritant.

Procedure

Day 1

1. Prior to this investigation, the plant was placed in total darkness for a minimum of two days. This was done so that the leaves would have depleted their stored supply of starch.
2. Obtain two 5 cm by 5 cm pieces of opaque black paper. Cut out a 1 to 2 cm wide shape of your choice in the centre of one piece of paper, creating a stencil. Leave the other piece intact.
3. Remove the plant from the dark room. Place the stencil on the upper surface of a healthy leaf. Place the second black piece of paper on the bottom of the same leaf. Secure the pieces of paper to the leaf using two paper clips (**Figure 1**).

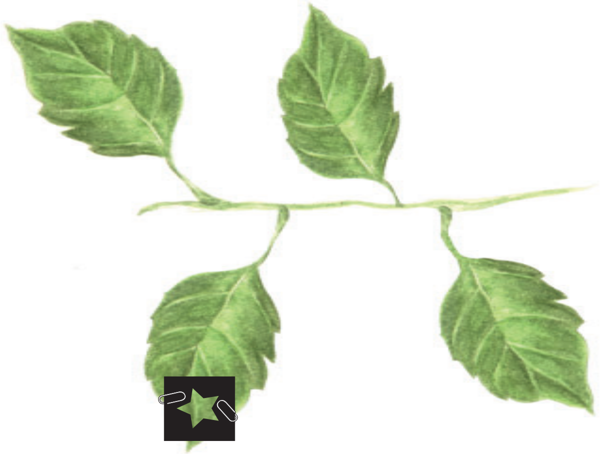


Figure 1 Mask a leaf with a stencil made from black paper.

4. Place the plant on a sunny window sill or under a bright light source for one or two days. Make sure that the covered leaf directly faces the Sun or another light source.

Day 2

5. Put on your safety goggles and lab apron.
6. Place 100 mL of water into the beaker and heat the water to a boil on the hot plate. Use a utility stand and ring clamp to secure the beaker.
7. Label the test tube with your name.
8. Add ethanol to the labelled test tube, to a depth of 6 cm. Place the test tube in a test-tube rack.

Ethanol is highly flammable. Do NOT conduct this experiment in a room with an open flame.

9. Remove the black paper from the leaf, and place the leaf in the test tube. Use a glass stirring rod to push the leaf into the alcohol and submerge it.
10. Use a test-tube holder to transfer the test tube to the beaker of boiling water.
11. Leave the test tube in the beaker until the leaf has lost its colour.
12. Use the test-tube holder to remove the test tube from the boiling water bath. Allow the test tube to cool for several minutes.
13. Carefully pour the warm ethanol into a container designated by your teacher.
14. Use forceps to remove the leaf from the test tube and place it in a Petri dish.
15. Rinse the leaf gently under running water, and pat it dry with a paper towel.
16. Apply several drops of Lugol's iodine solution to both the upper and lower surfaces of the leaf, ensuring that all parts of the leaf are saturated with the solution.
17. Allow the iodine-soaked leaf to sit in the Petri dish for 5 min. Observe and record the results by making a labelled drawing of the leaf.
18. Discard the plant leaf in the regular garbage. Dispose of the other materials according to your teacher's instructions.

Analyze and Evaluate

(a) What is the purpose of the Lugol's iodine solution? What does it indicate? T/I

(b) What differences did you notice in different parts of the leaf after you added the iodine? T/I

(c) What does this indicate about the difference between the areas of the leaves? T/I

(d) Why was it necessary to put the leaf in the ethanol solution? T/I

(e) Why did you attach the stencil to the leaf? K/U

(f) You may have noticed a relatively distinct boundary between the areas that were and were not exposed to the light. What does this suggest about the ability of starch to diffuse or move from one part of the leaf to another? Do you think your results would have differed if you had run your experiment for one or two weeks instead of one or two days? T/I

Apply and Extend

(g) In this investigation, you examined how exposure to light affects the process and products of photosynthesis. Propose another investigation in which you could learn how limiting a different environmental factor might affect photosynthesis. Consider examining a setting in your own community. T/I C A

Investigation 5.2.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

The Products of Photosynthesis

Early scientists had little or no concept of gases. To them, everything invisible was just air, and most felt that air was not even a substance. This viewpoint prevented scientists from detecting or even understanding gases such as oxygen and carbon dioxide, and it made learning about photosynthesis difficult. In this investigation, you will design an experiment to test for the production of oxygen gas during photosynthesis.

Purpose

To test for the production of oxygen gas during photosynthesis

Equipment and Materials

- aquarium or large clear jar
- test tubes
- light source
- beakers
- dissolved oxygen test kit
- plants and/or algae
- wooden splints
- tea candles

Procedure

SKILLS HANDBOOK A1, A2.4

Design a procedure to test for the production of oxygen gas during photosynthesis. When designing your procedure, consider how you might detect and/or measure oxygen gas. For example, can you measure differences in the volume of a gas in the air? Can you use a glowing splint to test for oxygen? Could you measure the oxygen level by observing how long a small candle is able to burn in a sealed chamber? Think about these methods and research other methods online.

Your experiment must be well designed. Ensure that the photosynthetic organism you have chosen can be provided with ideal conditions for performing photosynthesis, including adequate light, water, and carbon dioxide. Take into account the fact that photosynthetic organisms also perform aerobic cellular respiration and consume some oxygen gas. Remember to look for evidence of gas production and to include a method for testing for and identifying the gas.

Write up a formal procedure. Include any safety precautions. Obtain your teacher's approval before you begin this investigation.

Analyze and Evaluate

(a) Answer the following questions after you have carefully conducted your experiment and gathered and recorded your observations. T/I C
  (i) Describe your experimental design and how you observed and gathered evidence regarding oxygen gas production.
  (ii) Did you find evidence of gas production in your investigation?
  (iii) Were you able to identify the gas conclusively as oxygen? Explain.

(b) Which aspects of your experiment were the most challenging? How might you alter your procedure in the future to account for these challenges? T/I

(c) What factors, if any, seemed to influence the rate of oxygen production? T/I

(d) Explain how the results you witnessed are connected to activity within the cells and within the chloroplasts. At what step or steps in the photosynthetic pathway is oxygen gas produced? What must take place for this to happen? T/I

Apply and Extend

(e) Indoor plants perform photosynthesis as part of their living functions. Conduct research to answer these questions: T/I
  (i) Is the amount of oxygen production significant?
  (ii) Would the amount of carbon dioxide being released by plants inside a house at any particular time, such as during the night, constitute a health hazard to occupants?
  (iii) In the past, nurses were sometimes asked to remove all plants from a patient's room at night because it was thought that the plants would be competing with the patient for oxygen. Comment on why this practice is no longer standard in hospitals.

(f) Suppose you are asked to measure the concentration of oxygen and carbon dioxide gases in a rainforest canopy every hour for 24 h. Would you expect to see any particular pattern in your results? Explain your reasoning. T/I

WEB LINK

CHAPTER 5 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 210. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 210. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

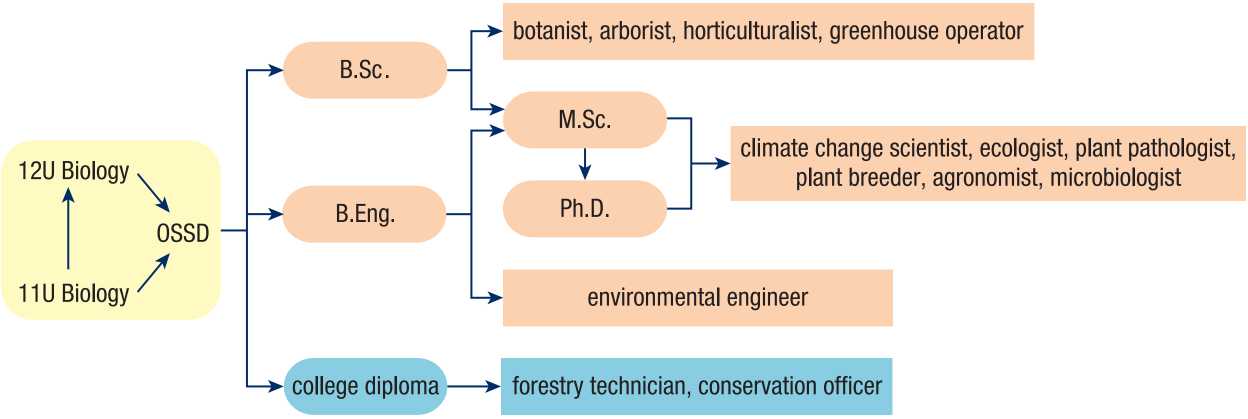
photoautotroph (p. 212)
light-dependent reactions (p. 212)
Calvin cycle (p. 213)
primary electron acceptor (p. 215)
antenna complex (p. 216)
reaction centre (p. 216)
absorption spectrum (p. 216)
action spectrum (p. 217)
photosystem I (p. 218)
photosystem II (p. 218)
rubisco (p. 227)
stomata (p. 231)
photorespiration (p. 231)
C_4 cycle (p. 232)
crassulacean acid metabolism (CAM) (p. 233)

CAREER **PATHWAYS**

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to photosynthesis that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also, outline how the career benefits society and the environment.


12U Biology
11U Biology
OSSD
B.Sc.
B.Eng.
college diploma
M.Sc.
Ph.D.
botanist, arborist, horticulturalist, greenhouse operator
climate change scientist, ecologist, plant pathologist, plant breeder, agronomist, microbiologist
environmental engineer
forestry technician, conservation officer

CAREER LINK

CHAPTER 5 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. The reactions of photosynthesis trap light energy and use it to convert carbon dioxide and water into another substance. What is this substance? (5.1) K/U
   (a) nitrates
   (b) ATP
   (c) carbohydrates
   (d) NAD^+
2. Light energy from the Sun is converted into chemical energy. Which process uses this chemical energy to synthesize organic compounds? (5.1) K/U
   (a) photosynthesis
   (b) chemosynthesis
   (c) cellular respiration
   (d) cellular autosynthesis
3. Which molecule acts as a catalyst for the reaction that incorporates carbon dioxide into organic compounds in the Calvin cycle? (5.2) K/U
   (a) chlorophyll
   (b) rubisco
   (c) ATP synthase
   (d) $NADP^+$ reductase
4. Which molecule oxidizes water in photosystem II? (5.2) K/U
   (a) P680
   (b) P680*
   (c) P700
   (d) $P680^+$
5. Who first identified the sequence of compounds that are created during the light-independent reactions? (5.3) K/U
   (a) Melvin Calvin
   (b) Jean Baptist van Helmont
   (c) Sir Hans Adolf Krebs
   (d) Lynn Margulis
6. How do CAM plants avoid photorespiration? (5.4) K/U
   (a) by running the Calvin cycle only at night
   (b) by opening their stomata only during the day
   (c) by fixing carbon in the form of malic acid during the night
   (d) by not using rubisco as a catalyst
7. Which statement about photorespiration is true? (5.4) K/U
   (a) It slows the Calvin cycle.
   (b) It uses ATP.
   (c) It catalyzes O_2 instead of CO_2.
   (d) all of the above
8. Which organelle is the site of photorespiration? (5.4) K/U
   (a) mitochondrion
   (b) chloroplast
   (c) Golgi body
   (d) nucleus
9. Which process of photosynthesis has attracted the attention of scientists working on alternative sources of energy? (5.5) K/U
   (a) synthesis of NADPH
   (b) synthesis of ATP
   (c) water splitting
   (d) chlorophyll *b* photon absorption
10. Which process requires light as a source of energy? (5.6) K/U
   (a) C_4 pathway
   (b) substrate-level phosphorylation
   (c) formation of malic acid
   (d) synthesis of NADPH
11. What is one similarity between photosynthesis and aerobic cellular respiration? (5.6) K/U
   (a) both involve ATP synthesis
   (b) both involve NADH synthesis
   (c) both produce CO_2
   (d) both produce glucose

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

12. The reactions of the Calvin cycle take place in the thylakoid membranes of chloroplasts. (5.1) K/U
13. Some processes of photosynthesis can occur without sunlight. (5.1) K/U
14. Light-dependent reactions take place in the thylakoid membranes of chloroplasts. (5.1) K/U
15. The splitting of water into electrons, protons, and oxygen gas involves photosystem I. (5.2) K/U
16. Melvin Calvin found that PGA and starch were produced within the first 5 s of photosynthesis in *Chlorella*. (5.3) K/U
17. In a C_4 plant, the Calvin cycle usually takes place in the bundle-sheath cells, which are found in the leaves of the plant. (5.4) K/U
18. Rubisco is highly efficient at fixing CO_2. (5.4) K/U
19. Photosynthesis can occur only in the chloroplasts of eukaryotic cells. (5.6) K/U

Go to Nelson Science for an online self-quiz.
WEB LINK

Knowledge

For each question, select the best answer from the four alternatives.

1. What is light used for in the light reactions of photosynthesis? (5.1) K/U
   (a) to synthesize NADPH and ATP
   (b) to synthesize hydrocarbons
   (c) to synthesize ADP and NADP$^+$
   (d) to fix carbon
2. Which of the following is a phase of photosynthesis? (5.1) K/U
   (a) Krebs cycle
   (b) Calvin cycle
   (c) photosystem I
   (d) photosystem II
3. Which product of photosynthesis was Engelmann looking for when he conducted his experiment with *Spirogyra*? (5.1) K/U
   (a) carbohydrates
   (b) oxygen
   (c) ATP
   (d) NADPH
4. What do three turns of the Calvin cycle produce? (5.2) K/U
   (a) 6 ATP
   (b) 2 G3P
   (c) 1 glucose
   (d) 3 RuBP
5. What is chemiosmosis in a chloroplast primarily responsible for? (5.2) K/U
   (a) hydrolysis of water
   (b) establishment of a proton gradient
   (c) recovery of NADP$^+$
   (d) synthesis of ATP
6. Why were Calvin's experiments particularly innovative? (5.3) K/U
   (a) He used a new technique of paper chromatography.
   (b) He used a radioisotope of carbon.
   (c) He used *Chlorella*.
   (d) all of the above
7. Which substance is a competitive inhibitor of rubisco? (5.4) K/U
   (a) carbon dioxide
   (b) oxygen
   (c) ATP
   (d) glucose
8. What is one of the drawbacks of CAM metabolism? (5.4) K/U
   (a) The Calvin cycle can only occur at night.
   (b) PEP must be regenerated, costing the plant ATP.
   (c) Carbon fixation efficiency is decreased in dry climates.
   (d) Large amounts of water are required during the day.
9. What is the goal of artificial photosynthesis? (5.5) K/U
   (a) to generate electricity directly
   (b) to generate hydrogen gas
   (c) to generate carbohydrates as a source of food
   (d) to generate hydrocarbons to replace oil
10. Which compound(s) does the electron transport system in plants use as an electron source? (5.6) K/U
    (a) water
    (b) oxygen
    (c) NADH and FADH$_2$
    (d) ATP and NADPH

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Action and absorption spectra are similar if the physiological process is linked. (5.1) K/U
12. Accessory pigments, when excited, become oxidized as they pass electrons to a primary electron acceptor. (5.1) K/U
13. One molecule that is required for photosynthesis is oxygen. (5.1) K/U
14. ATP synthesis takes place in the thylakoid space of a chloroplast. (5.1) K/U
15. The waste products from photosynthesis were necessary for the evolution of the diverse aerobic life forms on our planet. (5.2) K/U
16. In photosynthesis, light is responsible for providing the energy that is needed to remove electrons from NADPH. (5.2) K/U
17. Melvin Calvin determined that atmospheric CO$_2$ was incorporated directly into glucose during the Calvin cycle. (5.2) K/U
18. C$_4$ and CAM plants have an advantage over C$_3$ plants because they undergo much less photorespiration. (5.4) K/U
19. Only heterotrophs can carry out cellular respiration. (5.5) K/U
20. ATP synthase generates ATP by substrate-level phosphorylation. (5.6) K/U

Match each term on the left with the most appropriate description on the right.

21.	(a) 3-phosphoglycerate	(i)	reacts with CO_2
	(b) ATP	(ii)	is the enzyme that fixes CO_2
	(c) RuBP	(iii)	is produced during the reduction phase
	(d) G3P	(iv)	is a free energy source
	(e) rubisco	(v)	is reduced by NADPH (5.2) T/I
22.	(a) temporal separation	(i)	C_4 plants
	(b) bundle sheaths	(ii)	CAM plants
	(c) malate	(iii)	structure that opens at night in CAM plants
	(d) stomata	(iv)	location of the C_4 Calvin cycle
	(e) spatial separation	(v)	chemical that is used to stored CO_2 in CAM plants (5.2) T/I

Write a short answer to each question.

23. Develop an analogy to explain the role of accessory pigments in photosynthesis. (5.1) K/U C A
24. Use redox terms to summarize the net reaction of the Calvin cycle. (5.1) K/U T/I
25. Explain the significance of the products of the light reactions of photosynthesis, in relation to the Calvin cycle. (5.1) K/U
26. Do the light-dependent reactions and the Calvin cycle occur in the same part of the chloroplasts? Explain your answer. (5.2) K/U
27. What is the role of the non-protein organic groups in the light-dependent reactions of photosynthesis? (5.2) K/U
28. Outline the sequence of the redox reactions that take place in the electron transport system of the light reactions of photosynthesis. Begin with the absorption of a photon of light by photosystem II. (5.2) K/U
29. Explain why ferredoxin is such an important molecule for the Calvin cycle and other energy-dependent reactions in the chloroplasts. (5.2) K/U
30. Compare the role of ATP synthase in mitochondria and chloroplasts. (5.2) K/U
31. (a) Explain how $P680^+$ causes oxygen to be released into the atmosphere.
    (b) Explain how $P680^+$ causes the proton gradient to be established. (5.2) K/U
32. Develop a flow chart to show the major events in the experiment for which Melvin Calvin won the Nobel Prize. (5.3) K/U C
33. When the $CO_2 : O_2$ ratio drops, how does rubisco respond and what process is favoured? (5.4) K/U
34. Briefly describe two ways in which photorespiration is detrimental to a plant. (5.4) K/U
35. Explain why photorespiration is a greater problem in warmer climates than in cooler climates. (5.4) K/U
36. How do the C_4 cycle and spatial separation of the Calvin cycle help plants avoid photorespiration? (5.4) K/U
37. Describe the steps in the C_4 cycle. (5.4) K/U
38. What advantage do C_4 plants have in an arid climate? (5.4) K/U
39. Use a graphic organizer to compare and contrast the structure and function of mitochondria and chloroplasts. (5.5) K/U C

Understanding

40. Summarize how van Helmont's experiments laid the foundation for our understanding of plant physiology. (5.1) K/U
41. Would a green plant grow better under a green light or a red light? Explain your answer. (5.1) K/U T/I
42. Explain how photosynthesis is responsible for maintaining most of the life on Earth, with reference to the second law of thermodynamics. (5.1) K/U T/I
43. Using diagrams, explain how light is responsible for electrons entering the electron transport chain. (5.2) K/U T/I C
44. Is the standard photosynthesis equation, shown below, an accurate representation of the process of photosynthesis? Explain why. (5.2) K/U

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

45. What drives the electron transport chain in photosystem I and photosystem II? (5.2) K/U
46. Briefly define and summarize the process of chemiosmosis. (5.2) K/U
47. The term "dark reactions" was once used to describe the Calvin cycle. Use your current knowledge to suggest a possible reason why this term is no longer used. (5.2) K/U T/I
48. Three adaptations that are common to plants in arid climates make it more difficult for these plants to obtain enough carbon dioxide to keep the Calvin cycle running. Describe these adaptations. (5.4) K/U
49. How do the atmospheric concentrations of CO_2 and O_2 influence the rate of photorespiration? Explain why this is important. (5.4) K/U T/I
50. Where would you expect to find more C_4 plants: in southern Ontario or in northern Ontario? Explain your reasoning. (5.4) K/U T/I

51. Explain why C_4 plants, including CAM plants, are not more successful than C_3 plants. (5.4) K/U

52. What are the advantages of PEP carboxylase, compared with rubisco, in carbon dioxide fixation? (5.4) K/U

53. How is artificial photosynthesis different from the use of solar panels to generate electricity? (5.5) K/U

54. Identify and explain two ways in which the electron transport systems in photosynthesis and cellular respiration are different. (5.5) K/U T/I

55. What is the key feature that scientists are trying to harness in their development of artificial photosynthesis? (5.5) K/U

56. How are the light-dependent reactions of photosynthesis and the Calvin cycle dependent on each other? (5.5) K/U

57. Defend the following statement: "The development of photosynthetic organisms on Earth had a profound effect on Earth's atmosphere." (5.2, 5.6) K/U T/I

Analysis and Application

58. If you get a green grass stain on your clothing, it will eventually fade away. The green colour will disappear even if the clothes are never washed. What does this suggest about the chlorophyll pigment molecule? (5.1) K/U T/I A

59. Jan van Helmot's experiment was groundbreaking in its use of data analysis. (5.1) T/I
   (a) If you were to repeat his experiment using modern methods and equipment, how would you improve the experimental design?
   (b) How would you improve the variables to be measured?

60. Imagine that a Canadian space agency has recently hired you for your expertise in exobotany (alien plant life). Researchers have discovered a planet that is similar to Earth, but its atmosphere absorbs all the incoming red light. You have been hired because surface pictures of the planet show that plants are present. Write a press briefing that answers the following questions:
   - How might the environment on this planet have influenced the evolution of the photosynthetic plants that appear to be present?
   - What colour would you expect the photopigments of the plants to be?
   - Include a sketch or detailed description of what the plants might look like on this planet, as well as what they might look like if they were brought to Earth. (5.1, 5.2) K/U T/I C A

61. Design an experiment to find out which wavelengths of light would be most beneficial for the growth of a houseplant. (5.1) T/I

62. Chlorophyll was extracted from a spinach leaf, and the extract was placed in a spectrophotometer. The absorbance was recorded, as shown in **Table 1**. (5.1) K/U T/I C

Table 1

Wavelength (nm)	Absorbance	Wavelength (nm)	Absorbance
400	0.42	560	0.12
420	0.68	580	0.15
440	0.60	600	0.17
460	0.58	620	0.25
480	0.83	640	0.40
500	0.23	660	0.32
520	0.11	670	0.56
540	0.12	680	0.24

   (a) Construct a line graph, with wavelength along the *x*-axis and absorbance along the *y*-axis. Indicate the colours of the visible spectrum along the *x*-axis.
   (b) Which colour of light would be the least useful for viewing spinach? Which colour of light would be the most useful?
   (c) Compare your graph with the absorption spectrum in **Figure 1**. Label the peaks on your graph with the corresponding accessory pigments.

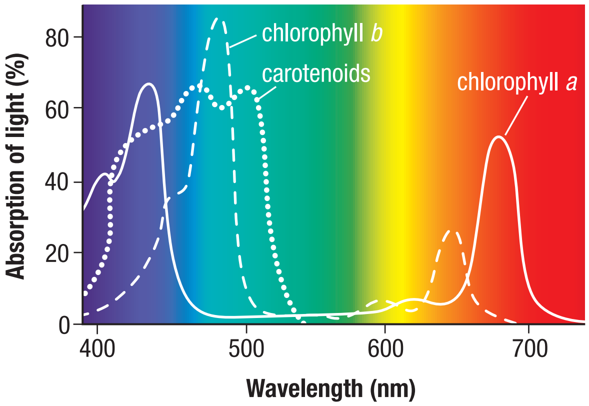


Figure 1

   (d) Explain why there are no peaks in the 500 to 620 nm range.
   (e) Which pigments are primarily responsible for the absorption in the 400 to 480 nm range?

63. Diuron (DCMU) is a herbicide that is no longer registered for use in Canada. It is a photosystem II inhibitor. What does this mean for a plant? (5.2) K/U T/I

64. A botanist takes a sample of chloroplasts from a plant. The plant has been thriving under normal conditions in the greenhouse. Upon examining the chloroplasts under the microscope, the botanist notices that they contain a very high concentration of ATP but very little NADPH. What are some possible explanations for the high concentration of ATP? (5.2) T/I

65. Several bean plants were kept in the dark for 72 h. They were then allowed to photosynthesize at a range of temperatures and at two different intensities of illumination. After 72 h, the plants were analyzed to determine the amount of sugar present in their leaves. The results are given in **Table 2**. (5.2) T/I

Table 2

Temperature (ºC)	Low light (mg of sugar per g of dry leaves)	High light (mg of sugar per g of dry leaves)
5	15	15
10	35	63
15	45	81
20	47	136
25	36	83
30	23	66
35	2	41
40	0	1
45	0	0

(a) Why were the plants kept in the dark?

(b) Interpret the results in terms of photosynthesis.

(c) Why did the plants in low light stop manufacturing sugar before the plants in high light?

66. All farmers want to maximize the amount of carbon fixed and minimize the amount of carbon used by their plants during respiration. Greenhouses provide a controlled environment in which conditions can be altered to maximize the amount of plant material that is produced. The graph in **Figure 2** shows how the relationship between respiration and photosynthesis can be compared. What conditions would you change to maximize the amount of photosynthesis that could occur, while minimizing the amount of respiration? (5.2) K/U T/I

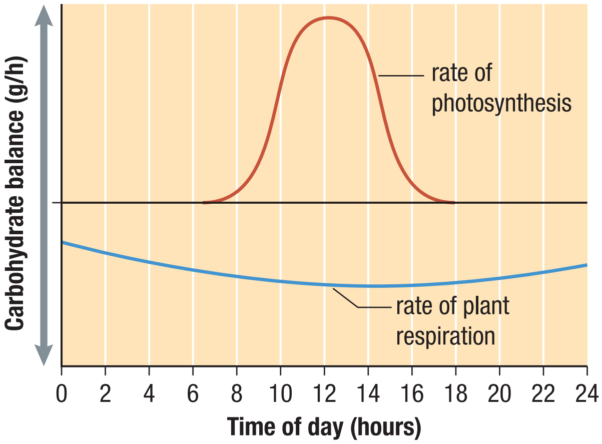


Figure 2 In this graph, the amount of carbohydrates being fixed is shown in the red graph and the amount of carbohydrates being catabolized is shown in the blue graph.

67. You have been recruited to identify several new plants that were sent to a lab. You have been asked to group them as C_3 plants, C_4 plants, and CAM plants. You have access to equipment to perform Calvin's experiment, a spectrophotometer, a greenhouse, a magnifying glass, and nail polish. Explain how you could use each of these pieces of equipment to distinguish between the three types of plants. (5.2, 5.3) T/I A

68. Scientists routinely create knockout organisms to determine the function of a gene. Suppose that a plant has the gene responsible for $NADP^+$ reductase enzyme "knocked out." What effect would this have on the cells of the plant, in terms of their ability to perform each of the following processes? (5.3) K/U T/I

(a) non-cyclic ATP synthesis

(b) cyclic ATP synthesis

(c) Calvin cycle

69. The lowland areas of the Galapagos Islands are very arid and thus are home to many cacti and other succulent species of plants (**Figure 3(a)**). The highlands of the Galapagos, in contrast, are cool and moist. They are covered in thick, green vegetation, with few succulents (**Figure 3(b)**). Use your understanding of photorespiration to account for this pattern of plant distribution. (5.4) K/U T/I A

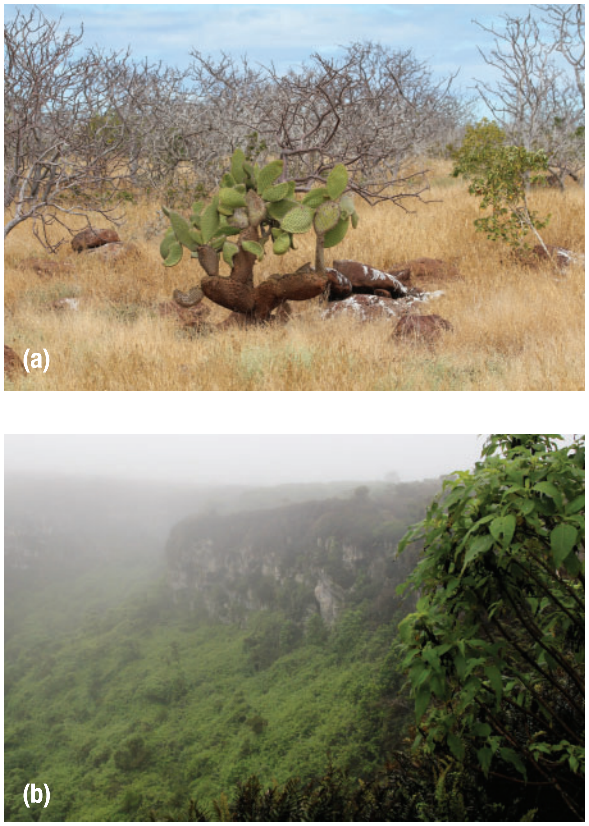


Figure 3

70. Imagine that you are investigating a new species of plant. You decide to use Melvin Calvin's experiment as your inspiration. You take a sample of leaves from the plant and expose them, using the same methods that Calvin used in his experiments. When you examine the chromatograms, you notice something strange. The plants in your control (the plants that were not exposed to light) show the presence of radioactive malic acid but no radioactive G3P. What can you infer from this observation? (5.3, 5.4) K/U T/I

71. **Figure 4** shows the rate of photosynthesis versus ambient CO_2 concentration for a C_3 plant and a C_4 plant. (5.2, 5.4) K/U T/I
    (a) Explain the difference in the two CO_2 compensation points. The compensation point is where the rate of photosynthesis equals the rate of cellular respiration.
    (b) Why does the rate of C_4 plant photosynthesis rise faster than the rate of C_3 photosynthesis as the CO_2 concentration increases?
    (c) What do these curves tell you about the relative success of C_3 and C_4 plants in an environment where the CO_2 concentration is increasing?

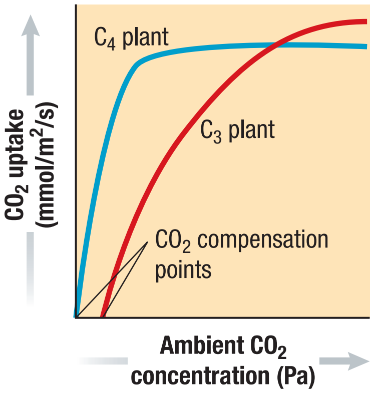


Figure 4 Rate of photosynthesis versus ambient CO_2 concentration

72. Two fields contain a variety of different weeds: some undergo C_3 photosynthesis, others undergo C_4 photosynthesis, and the rest undergo CAM photosynthesis. One field is sprayed with a herbicide than inhibits rubisco. The other field is sprayed with a herbicide that inhibits PEP carboxylase. After one week, what would you expect to see happening in the two fields? (5.2, 5.4) K/U T/I

73. Explain why CAM plants grow much more slowly than C_3 plants when each type of plant is placed under ideal growing conditions. (5.2, 5.4) K/U T/I

74. You are working at a greenhouse that has a small store inside it. You decide that the temperature in the store is too hot. You turn on the air conditioning to lower the temperature in the store to 25 °C, while leaving the greenhouse at the original temperature of 40 °C. One week later, you notice that there has been a change in the plants in the store, compared with the plants in the rest of the greenhouse. (5.2, 5.4) K/U T/I
    (a) Copy **Table 3** into your notebook and complete it by describing the appearance of the plants in the store and the plants in the greenhouse.

Table 3

Type of plant	Store	Greenhouse
C_3		
C_4		

    (b) Summarize and explain your observations. Assume that both groups of plants have received the same water, fertilizer, and light.

Evaluation

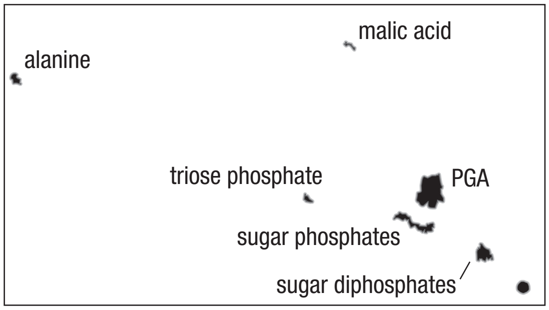
75. Use a Venn diagram to compare and contrast the structure of chlorophyll and carotenoid molecules, as well as their ability to transfer energy to the primary electron acceptors after absorbing light energy. (5.1) K/U C

76. Chlorophyll *a* is the only pigment that contributes electrons directly to the primary electron acceptor. Knowing this, explain why plants have evolved to contain chlorophyll *b* and the accessory pigments. (5.1) K/U T/I

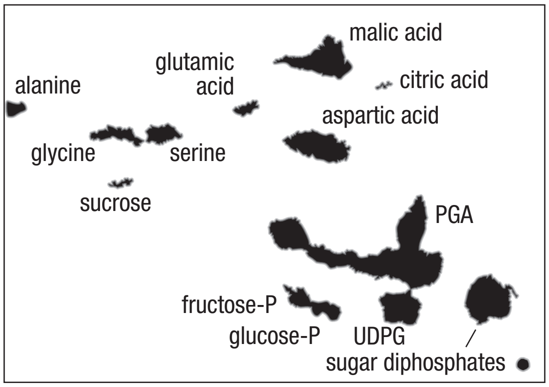
77. Rubisco is used by almost all photoautotrophs. Some scientists claim that it is the most important enzyme in the biosphere. Defend or refute this claim, using evidence from the chapter, as well as your prior knowledge. (5.2) K/U T/I C

78. (a) Describe the key differences between cyclic electron transport and non-cyclic electron transport.
    (b) Create a graphic organizer that highlights the differences between these two processes. (5.2) K/U C

79. Refer to the chromatograms in **Figure 5** to answer the following questions. (5.2, 5.3) K/U T/I A



(a) pattern after 5 s of photosynthesis with *Chlorella* in $^{14}CO_2$



(b) pattern after 30 s of photosynthesis with *Chlorella* in $^{14}CO_2$

Figure 5

(a) What chromatogram evidence suggests that 6-carbon and 12-carbon sugars are not produced "immediately" once photosynthesis begins?

(b) What evidence suggests that PGA may be one of the first intermediate compounds in the Calvin cycle? (Calvin used the label PGA to refer to the compound 3-phosphoglycerate.)

(c) Figure 7 on page 226 focuses on G3P, a triose phosphate. What chromatogram evidence in Figure 5 above suggests that G3P is produced rapidly during photosynthesis but is quickly converted to larger carbohydrates?

80. Heterotrophs need autotrophs to survive, but do autotrophs need heterotrophs to survive? Explain and justify your answer. (5.6) K/U T/I A

81. Climate change is causing average global temperatures to rise and is linked to an increasing CO_2 level. How might this influence the abundance of C_3, C_4, and CAM plants? (5.6) K/U T/I

Reflect on Your Learning

82. Why do you think alternative pathways for carbon fixation evolved over time? K/U T/I

83. Artificial photosynthesis is an interesting technology. In your opinion, how should this technology be pursued in the future? Give at least three reasons to support your opinion. K/U T/I A

84. What was the most surprising thing that you learned about photosynthesis? How has that changed your view of plants and their metabolic pathways? T/I A

85. Has what you learned in this chapter changed your views on plants and how we as humans interact with them? What could you do differently in your living environment to help promote plants? T/I A

Research

WEB LINK

86. In an effort to reduce greenhouse gases, scientists are investigating the use of bioscrubbers for capturing CO_2 emitted from large-scale CO_2 sources (such as power plants) that rely on the burning of fossil fuels. Research the design and impact of bioscrubbers. T/I C A

(a) Based on your research, design a system that could be used on a small scale, at your school or at home.

(b) Develop a multimedia presentation that highlights the strengths and weaknesses of your design and explains how it could change the environmental footprint of your school or home.

87. Create a list of foods that you eat regularly. From this list, identify the five most important plants in your diet. Research the growing conditions for these five plants, and determine whether they are C_3, C_4, or CAM plants. K/U T/I A

88. Photosynthesis is extremely important to our daily life, yet it is only about 1 % efficient. Scientists are using a variety of techniques to investigate and manipulate photosynthesis in plants. Conduct online research to learn about this area of plant research. Use your research to answer the following questions. K/U T/I A

(a) What advances are being made in this area of plant research?

(b) How will these advances benefit society?

(c) New technologies are being developed to improve the efficiency of photosynthesis. What are some possible future applications of these technologies?

Putting Knowledge to Work

In this unit, you learned about the important metabolic processes of photosynthesis, aerobic and anaerobic cellular respiration, and fermentation. Photosynthesis converts light energy into chemical energy, which can then be used during aerobic and anaerobic cellular respiration and fermentation to extract the energy from molecules such as carbohydrates, lipids, and proteins. All organisms depend on these processes to obtain their energy.

This Unit Task has two parts. In Part A, you will carry out a controlled experiment to examine the effect of one abiotic factor on one of these processes. In Part B, you will research one biochemical process related to cellular respiration, fermentation, or photosynthesis, and examine its application in today's society.

Part A: Exploring Metabolic Processes

In Part A of this Unit Task, you will select one metabolic process. You will then design and carry out a controlled experiment to determine the effect of one abiotic factor on the process.

Purpose

To understand how abiotic factors affect the metabolic processes of fermentation, photosynthesis, or aerobic cellular respiration

Testable Question

Choose one of the following testable questions, or devise another question, with your teacher's approval:

1. What is the ideal temperature for the fermentation of glucose by yeast?
2. How does the colour of light influence the rate of photosynthesis in plants?
3. How does temperature affect the rate of aerobic cellular respiration in crickets?

Hypothesis

Transform your testable question into a hypothesis. Remember that a hypothesis states a prediction and a possible explanation for the outcome. Use what you have learned in this unit to formulate your hypothesis.

Procedure

1. Research and design a controlled experiment to test your hypothesis. Include a list of materials and appropriate safety precautions. Obtain your teacher's approval to carry out your experiment.
2. Perform your experiment, being careful to follow the safety procedures and to collect all the relevant data.
3. Analyze the data using tables and graphs where necessary.
4. Write up your results and conclusions in a formal lab report.

Part B: Exploring Applications of Metabolic Processes

Many biochemical processes have applications, such as the synthesis of biofuels (**Figure 1**) or the production of cheese. In Part B of this Unit Task, you will select one such application and research and discuss its implications for society and the environment.

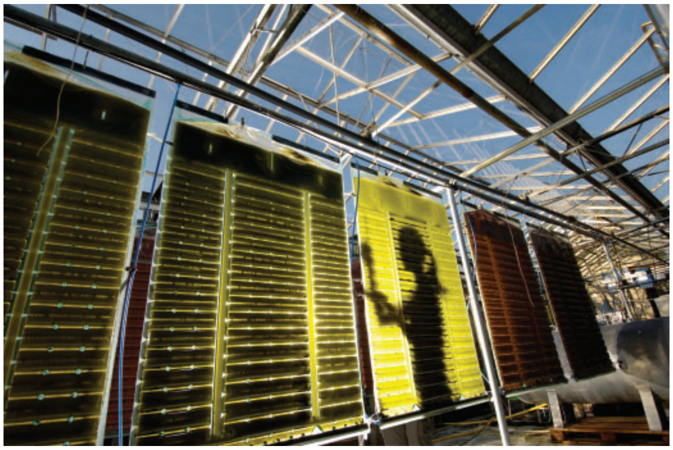


Figure 1 Algae biofuel production

Procedure

5. From the list below, choose a biochemical application related to cellular respiration, fermentation, or photosynthesis. Alternatively, ask your teacher to approve another related topic:
   - bioremediation (for example, cleaning up oil spills or mine tailings)
   - sewage treatment
   - solid waste management
   - biofuel production
   - synthesis of drugs
   - production of beer or wine
   - production of cheese
   - new commercially valuable natural products

6. Investigate the science behind the product or process. Consider the following questions:
   - How does it work?
   - What are the reactants (feed stock)?
   - What are the products?
   - Are there any risks associated with this product or procedure? How might these risks be managed?
   - Do you think the use of this application is beneficial to society and the environment as a whole? Explain why or why not. WEB LINK
7. Describe the biochemical pathway used in the application. Support your description with drawings or physical models of the compounds.
8. Present your findings in the format of your choice. You may wish to do a 5 min presentation, create a video documentary, or prepare a one- to two-page written report. Be sure to support your findings and suggestions with data, and cite your reputable, published scientific sources.

Analyze and Evaluate

Part A: Exploring Metabolic Processes

(a) Did your experimental results support your hypothesis? Speculate as to why they did or did not. T/I

(b) What factors were controlled in your experiment? Were there any factors that were beyond your control? T/I

(c) Where did the energy come from in the metabolic process that you explored? T/I

Part B: Exploring Applications of Metabolic Processes

(d) Where did the energy come from in the application that you explored in Part B? K/U T/I

Apply and Extend

(e) (i) What knowledge gaps exist in the topic you chose to investigate in Part A?

(ii) What additional research needs to be conducted to increase our understanding of this topic? T/I A

(f) (i) What knowledge gaps exist in the topic you chose for Part B?

(ii) What additional research needs to be conducted to help us better understand this topic in the future? T/I A

(g) Why might the conservation of biodiversity, even when it applies to micro-organisms, be important in relation to the topic you explored in Part B? T/I A

(h) If you were given $1 million in research funding to investigate a question related to metabolic processes, such as the processes you explored in Parts A and B, what research question would you explore, and why? How would you go about completing this task? A

WEB LINK

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

✓ Demonstrate understanding of the metabolic process that you explored in Part A.

✓ Demonstrate understanding of the relationship between the abiotic factor you selected and the metabolic process that you explored in Part A.

✓ Demonstrate knowledge of the biochemical process that you investigated in Part B.

Thinking/Investigation

✓ Formulate a hypothesis and conduct a controlled experiment in Part A.

✓ Draw conclusions based on data collected in your experiment in Part A.

✓ Collect, synthesize, and organize information in Part B.

✓ Demonstrate understanding of the societal and/or environmental implications of the process you explored in Part B.

✓ Analyze the information and come to a decision about the risks and benefits of the application.

Communication

✓ Synthesize findings in a report.

✓ Communicate findings in audiovisual format using a variety of multimedia tools.

✓ Communicate your findings clearly and concisely.

Application

✓ Evaluate the benefits and risks of the biochemical processes you selected.

UNIT 2 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What is the most important form of stored energy for organisms? (3.1) K/U
   (a) chemical potential energy
   (b) kinetic energy
   (c) gravitational potential energy
   (d) thermal energy
2. Which of the following is a type of energy released in a chemical reaction? (3.1) K/U
   (a) thermal
   (b) light
   (c) mechanical
   (d) all of the above
3. What is the name of the process that involves the continuous breakdown and re-synthesis of ATP? (3.2) K/U
   (a) citric acid cycle
   (b) chemiosmosis
   (c) phosphorylation
   (d) ATP cycle
4. Which enzyme catalyzes the breakdown of amylose to maltose? (3.3) K/U
   (a) maltase
   (b) lactase
   (c) catalase
   (d) amylase
5. Without enzymes, what would happen to metabolism reactions in living organisms? (3.3) K/U
   (a) They would not occur.
   (b) They would be very slow.
   (c) They would generate excess products.
   (d) They would proceed too quickly.
6. Which of the following is a product of the complete oxidation of an organic molecule? (3.4) K/U
   (a) CO_2
   (b) O_2
   (c) $C_6H_{12}O_6$
   (d) CH_4
7. Which term refers to cellular respiration that occurs in the presence of oxygen? (4.1) K/U
   (a) aerobic respiration
   (b) anaerobic respiration
   (c) fermentation
   (d) catabolic respiration
8. Which of the following is a high-energy molecule produced by the citric acid cycle? (4.2) K/U
   (a) NADH
   (b) ATP
   (c) $FADH_2$
   (d) all of the above
9. The following chemicals are involved in electron transport. Which of these chemicals has the strongest pull on electrons? (4.2) K/U
   (a) NADH
   (b) $FADH_2$
   (c) O_2
   (d) ubiquinone
10. For each $FADH_2$ that is oxidized by the electron transport chain, how many ATP molecules are synthesized? (4.3) K/U
    (a) 2
    (b) 0
    (c) 38
    (d) 4
11. Which of the following best describes metabolic rate? (4.3) K/U
    (a) a change in energy production
    (b) the number of citric acid cycles completed per second
    (c) the amount of energy consumed over a specified time in an organism
    (d) the average amount of work done by an organism
12. What are yeasts? (4.4) K/U
    (a) anaerobes
    (b) aerobes
    (c) facultative anaerobes
    (d) facultative aerobes
13. During photosynthesis, what can happen to the energy from an excited electron? (5.1) K/U
    (a) It can be emitted as thermal energy.
    (b) It can be transferred to a pigment molecule.
    (c) It can be transferred to an electron acceptor.
    (d) all the above
14. When chlorophyll undergoes fluorescence, light is emitted. Which law does the light follow? (5.1) K/U
    (a) first law of thermodynamics
    (b) second law of thermodynamics
    (c) third law of thermodynamics
    (d) both the first law and the second law of thermodynamics

15. Which reaction(s) do light-dependent processes involve? (5.1) K/U
    (a) oxidation
    (b) reduction
    (c) carbon fixation
    (d) oxidation and reduction
16. What is the name of the process in which ATP is synthesized from ADP and P_i using free energy? (5.2) K/U
    (a) chemiosmosis
    (b) protonic transfer
    (c) hydrolysis
    (d) mitochondrial respiration
17. Which of the following options lists the complexes in the thylakoid membrane in the order used in linear electron transport? (5.2) K/U
    (a) photosystem II, cytochrome complex, photosystem I
    (b) photosystem I, cytochrome complex, photosystem II
    (c) photosystem I, photosystem II, cytochrome complex
    (d) photosystem II, photosystem I, cytochrome complex
18. Based on the following reaction, how many photons need to be absorbed during the light reactions to produce a single molecule of O_2? (5.2) K/U

    $2\ H_2O \rightarrow 4\ H^+ + 4\ e^- + O_2$

    (a) 2
    (b) 4
    (c) 8
    (d) 12
19. Which substrate serves as an alternative to rubisco? (5.4) K/U
    (a) O_2
    (b) H_2
    (c) NADH
    (d) $FADH_2$

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

20. The first law of thermodynamics states that energy cannot be created or destroyed, but can only be converted from one form to another. (3.1) K/U
21. All energy exists in three states: kinetic, potential, and gravitational. (3.1) K/U
22. The energy that is needed to break a bond reflects the relative strength of the bond. (3.1) K/U
23. Energy coupling is the total energy that is generated by two paired reactions. (3.2) K/U
24. Enzymes speed up a reaction by lowering the energy of the products. (3.3) K/U
25. Rapid combustion and controlled oxidation are both exergonic reactions, but they differ in the overall change in free energy. (3.4) K/U
26. Oxidation refers to the loss of electrons, and reduction refers to the gain of electrons. (3.4) K/U
27. Fermentation occurs in the presence of oxygen. (4.1) K/U
28. Cellular aerobic respiration is an essential part of the citric acid cycle. (4.1) K/U
29. Glycolysis is an aerobic process. (4.2) K/U
30. By the end of the citric acid cycle, all the carbon in glucose has been completely oxidized and released as CO_2. (4.2) K/U
31. The two molecules of pyruvate that are synthesized during glycolysis contain approximately 75 % of the energy from the original molecule of glucose. (4.2) K/U
32. In eukaryotes, the reactions of the citric acid cycle occur in the cytosol. (4.2) K/U
33. Many prokaryotes have respiratory electron transport chains. (4.4) K/U
34. Cellular aerobic respiration occurs in plants. (5.1) K/U
35. Green algae are classified as consumers. (5.1) K/U
36. The organic molecules of plants are assembled using the carbon that has been fixed during photosynthesis. (5.1) K/U
37. Photosystem II can operate independently of photosystem I in a cyclic pathway. (5.2) K/U
38. The enzyme rubisco converts carbohydrates into CO_2. (5.2) K/U
39. Melvin Calvin used both chromatography and radioactive isotopes to complete his research on photosynthesis. (5.3) K/U
40. Plants, such as pineapple, that use the Crassulacean acid metabolism (CAM) pathway fix CO_2 at different times of the day than plants that use C_3 carbon fixation do. (5.4) K/U
41. An advantage of the C_4 cycle is that it provides the plant with a higher oxygen concentration for the Calvin cycle reactions. (5.4) K/U

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which statement describes a chemical reaction in which entropy decreases? (3.1) K/U
   (a) Liquids react to form gaseous products.
   (b) The total number of reactant molecules is greater than the total number of product molecules.
   (c) Solids react to form liquids or gases.
   (d) Simple products result from the breakdown of larger complex reactants.
2. Which of the following does NOT occur during ATP hydrolysis? (3.2) K/U
   (a) Inorganic phosphate forms.
   (b) The terminal phosphate group breaks off.
   (c) Adenosine diphosphate forms.
   (d) A water molecule forms.
3. Which of the following is a function of enzymes? (3.3) K/U
   (a) to speed up the rate of a reaction
   (b) to change the ΔG of a reaction
   (c) to supply free energy for a reaction
   (d) to cause an endergonic reaction to proceed spontaneously
4. Some reactions involve the transfer of electrons from one molecule to another. What are these reactions called? (3.4) K/U
   (a) neutralization reactions
   (b) synthesis reactions
   (c) redox reactions
   (d) dehydration reactions
5. What is the term for organisms that can survive with or without oxygen? (4.1) K/U
   (a) obligate anaerobes
   (b) obligate aerobes
   (c) facultative anaerobes
   (d) facultative aerobes
6. What causes the transfer of electrons through the electron transport chain? (4.2) K/U
   (a) an initial “push” from NADH
   (b) the increasing electronegativity of carriers and the terminal oxygen
   (c) protons moving across the membrane
   (d) an electromotive force
7. Most metabolic pathways are regulated by a process of supply and demand. What is the name of the process? (4.3) K/U
   (a) photosynthesis
   (b) oxidation
   (c) feedback inhibition
   (d) glycolysis
8. How would you describe lactate fermentation? (4.4) K/U
   (a) as efficient as alcohol fermentation
   (b) less efficient than alcohol fermentation
   (c) more efficient than alcohol fermentation
   (d) an endothermic reaction
9. Which of the following are found within chloroplasts? (5.1) K/U
   (a) stroma
   (b) thylakoid membrane
   (c) chlorophyll
   (d) all of the above
10. Where do the light-independent reactions of photosynthesis occur? (5.2) K/U
    (a) within the thylakoid membrane of the chloroplasts
    (b) within the thylakoid lumen of the chloroplasts
    (c) within the chlorophyll
    (d) within the stroma of the chloroplasts
11. Which of the following is a characteristic of the C_3 cycle? (5.4) K/U
    (a) reduces the rate of photorespiration
    (b) provides an additional carbon fixation pathway
    (c) inhibits rubisco oxygenation reactions
    (d) is common to plants in cool, wet climates
12. Which enzyme do the inner membranes of both mitochondria and chloroplasts contain? (5.6) K/U
    (a) ubiquinone
    (b) $NADP^+$ reductase
    (c) ferredoxin
    (d) ATP synthase

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

13. The farther away an electron is from the nucleus of an atom, the more kinetic energy it has. (3.1) K/U
14. Reactions with a negative ΔG are considered non-spontaneous. (3.3) K/U
15. The more electronegative an atom is, the greater the tendency for it to undergo oxidation. (3.4) K/U

16. Cellular respiration cannot occur in prokaryotes because they do not have mitochondria. (4.1) K/U

17. As reactants progress through the electron transport chain, they gain free energy. (4.2) K/U

18. Fatty acids must be metabolized to pyruvate before they can enter the citric acid cycle. (4.3) K/U

19. Anaerobic cellular respiration provides cells with more energy per gram of glucose than aerobic cellular respiration. (4.4) K/U

20. The energy that is released when an electron returns to the ground state is equal to the energy that it absorbed when it was promoted. (5.1) K/U

21. Cyclic photophosphorylation has a negative impact on the ability of chloroplasts to undergo the Calvin cycle because it is a source of additional NADPH. (5.2) K/U

22. The flow of electrons along the photosynthetic electron transport chain establishes a proton gradient across the thylakoid membrane. (5.2) K/U

23. The light-dependent reactions of photosynthesis take place within the stroma of chloroplasts. (5.2) K/U

24. Photorespiration increases the efficiency of the Calvin cycle by producing ATP and catabolizing hydrocarbons. (5.4) K/U

Match each term on the left with the most appropriate description on the right.

25. (a) chemiosmosis
    (b) citric acid cycle
    (c) glycolysis
    (d) electron transport chain
    (e) pyruvate oxidation

    (i) synthesizes pyruvate and a small amount of ATP
    (ii) creates a proton gradient across the inner mitochondrial membrane
    (iii) generates ATP, NADH, and $FADH_2$
    (iv) forms acetyl-CoA, CO_2, and NADH
    (v) synthesizes ATP as a result of the proton-motive force (4.1) K/U

Write a short answer to each question.

26. Write the equation for the hydrolysis of ATP. (3.2) K/U C

27. Explain why ATP contains large amounts of free energy. (3.2) K/U

28. State and summarize the four stages of cellular aerobic respiration. (4.1) K/U

29. List the key steps that take place from the end of glycolysis until the beginning of the citric acid cycle. (4.2) K/U

30. Explain how fermentation reactions allow glycolysis to occur. (4.4) K/U

31. Describe the three possible fates of an “excited” electron that belongs to a pigment molecule. Support your description with diagrams. (5.1) K/U C

32. List three accessory pigments, and explain how each pigment contributes to developing the action spectra. (5.1) K/U

33. What causes leaves to change colour in the fall? (5.1) K/U

34. What is the function of a photosystem? (5.1) K/U

35. Would you expect plants to grow well in green light? Explain why or why not. (5.1) K/U T/I

36. Describe the three processes that create a proton gradient across the thylakoid membrane during photosynthesis. (5.2) K/U

37. List the three different forms, or states, of the chlorophyll molecule P680, and describe the differences among these forms. (5.2) K/U

38. Compare the biochemical activity of CAM plants during the day with their activity at night. (5.4) K/U T/I

Understanding

39. **Figure 1** shows a graph of the changes in energy during an unidentified reaction. (3.1) K/U T/I
    (a) Is this an endothermic reaction or an exothermic reaction?
    (b) Explain what is happening, in terms of energy, as the reaction progresses.

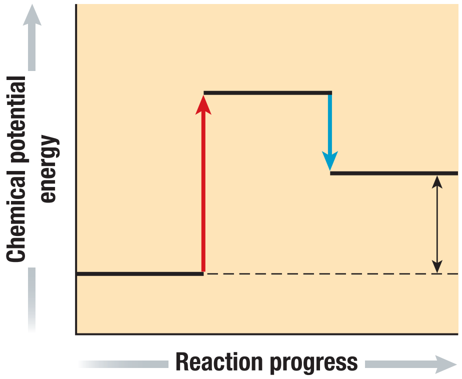
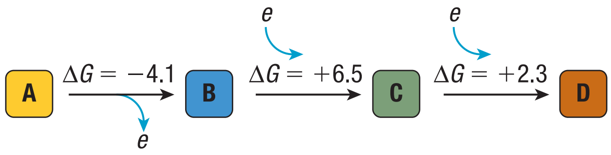


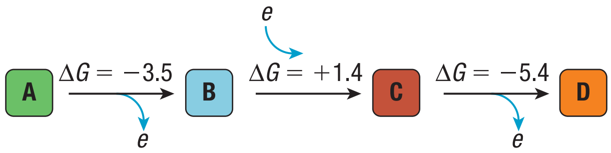
Figure 1

40. Outline, using entropy terms, how sweating cools humans. (3.1) K/U

41. Refer to **Figure 2** and **Figure 3**. (3.1) K/U T/I C



(a) overall ΔG = +4.7 kcal/mol



(b) overall ΔG = −7.5 kcal/mol

Figure 2

(a) Which pathway in Figure 2 is likely to be catabolic? Which pathway is likely to be anabolic? Explain your reasoning.

(b) Which pathway in Figure 2 is represented by the free energy diagram in Figure 3?

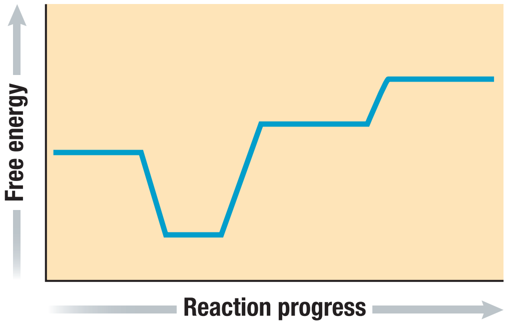


Figure 3

42. **Figure 4** shows a graph of the changes in energy during an unidentified reaction. (3.1) K/U T/I

(a) Is this an exergonic reaction or an endergonic reaction?

(b) Explain what is happening, in terms of energy, as the reaction progresses.

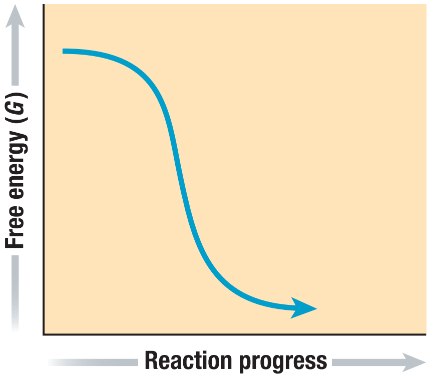


Figure 4

43. Explain the three major mechanisms that enzymes use to reduce the activation energy of a reaction. Support your explanation with diagrams. (3.3) K/U C

44. Describe the property of lipids that makes them a better energy source than proteins or carbohydrates. Refer to bond energy in your description. (3.4) K/U

45. Compare substrate-level phosphorylation with oxidative phosphorylation. Which process is responsible for generating more ATP? (4.1) K/U T/I

46. Create a flow chart to demonstrate how the electron transport chain in mitochondria is driven by oxygen. (4.2) K/U C

47. Describe how the proton-motive force is established during aerobic cellular respiration, and explain its importance in ATP synthesis. (4.2) K/U

48. In aerobic cellular respiration, how is the energy that is released during electron transport used to establish a source of potential energy across the inner mitochondrial membrane? (4.2) K/U

49. Identify the controlling factor that prevents a cell from producing more energy than it needs, and explain its mechanism of operation. (4.3) K/U

50. What would happen if your cells were not able to undergo lactate fermentation? (4.4) K/U T/I

51. Buttermilk is produced by the addition of certain bacteria to milk. These bacteria undergo lactate fermentation. Explain how this process is likely to affect the flavour of buttermilk. (4.4) T/I

52. Compare the energy output of fermentation with the energy output of aerobic cellular respiration. Which process produces less energy from one molecule of glucose? Explain why. (4.4) K/U

53. Using diagrams, explain how uncoupling decreases the efficiency of aerobic cellular respiration. (4.5) K/U C

54. Two plants are stored under different conditions. One plant is stored in a room with a lot of light, while the other plant is stored in a room with very little light. Which plant would you expect to contain a higher level of starch? Explain your reasoning. (5.1) K/U T/I A

55. Deciduous trees lose their leaves in the winter. How do they survive without the ability to photosynthesize? (5.1) K/U

56. Compare and contrast chemiosmosis in photosynthesis with chemiosmosis in cellular respiration. (5.2) K/U T/I

57. (a) Describe the optimal conditions under which photorespiration is likely to occur in C_3 plants.

(b) What effect does the resulting pathway have on the efficiency of photosynthesis? (5.4) K/U

58. Explain how the relative number of stomata in different species of plants may influence the success of the plants in different environments. (5.4) K/U A

Analysis and Application

59. A student is researching the nutrient content of plant tissues using a newly discovered hydrolase enzyme (an enzyme that catalyzes the hydrolysis of some organic compounds). The student prepares a suspension of several plant tissue extracts, which contain a variety of nutrients. The student must then place the suspension under the following four sets of conditions for 24 h:

(i) suspension at 5 °C
(ii) suspension at 35 °C
(iii) suspension + hydrolase enzymes at 5 °C
(iv) suspension + hydrolase enzymes at 35 °C (3.1) T/I

(a) Predict the rate of activity under each set of conditions. Provide reasons for your predictions.

(b) What chemical products might you expect to be produced under the most active conditions? Explain your reasoning.

60. The complete oxidation of glucose to carbon dioxide and water releases 2870 kJ/mol of available energy. Respiration only captures 930 kJ/mol of available energy. (3.1) K/U T/I

(a) What is the effective efficiency of aerobic cellular respiration?

(b) Where does the rest of the energy go?

61. **Figure 5** shows a free energy diagram. (3.1) K/U T/I C

(a) Explain why Figure 5 does not represent cellular respiration.

(b) Sketch a free energy diagram that accurately represents cellular respiration.

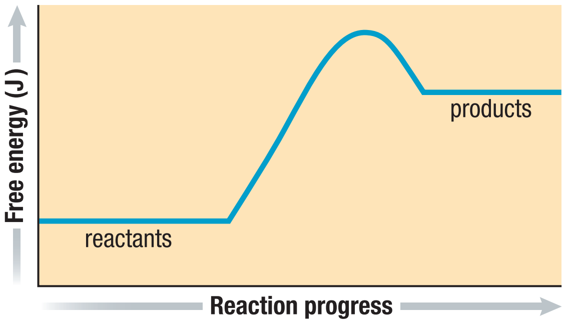


Figure 5

62. The two graphs in **Figure 6** represent energy profiles of chemical processes that take place in cells. (3.1) K/U T/I

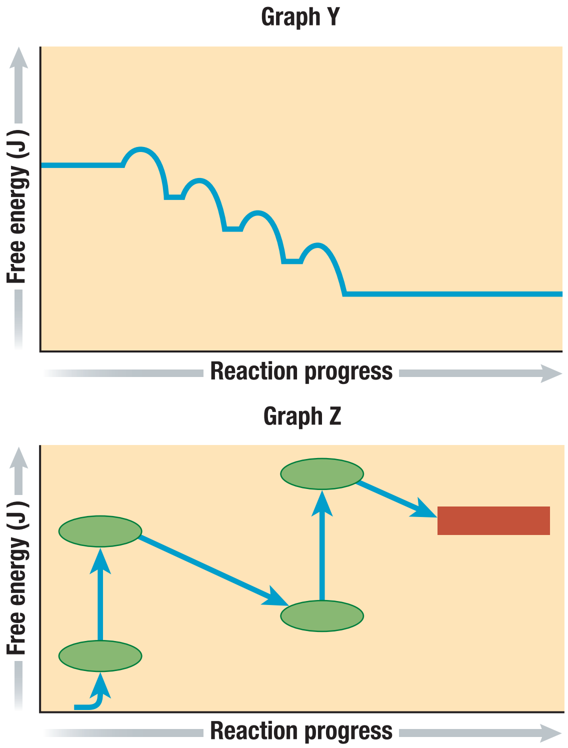


Figure 6

(a) Identify the process that is represented in each graph.

(b) Identify each graph as either endothermic or exothermic.

63. **Figure 7** shows a free energy diagram of a chemical reaction that occurs without an enzyme. (3.3) K/U T/I C

(a) Copy Figure 7 into your notebook. Label the arrows and the transition state. Also indicate any changes in free energy that take place during the reaction.

(b) Is the reaction spontaneous? Explain.

(c) On the same graph, sketch the reaction that occurs when an enzyme is added. Include the same labels you added to your diagram in (a). Explain any differences in the appearance of your two lines.

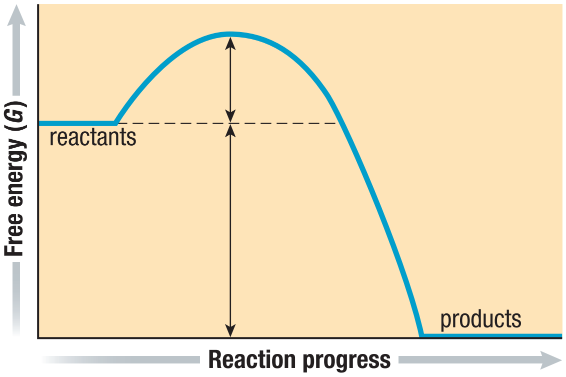


Figure 7

64. Use your current knowledge of enzymes to write a short paragraph about the role of enzymes in industry. (3.3) K/U A

65. Account for the observation that sucrose does not break down into fructose and glucose when left at room temperature for a very long time, despite the fact that this reaction is classified as "spontaneous." (3.3) K/U

66. **Figure 8** shows two lipids. Identify which of these two lipids has less available energy, and explain why. (3.4) K/U T/I A

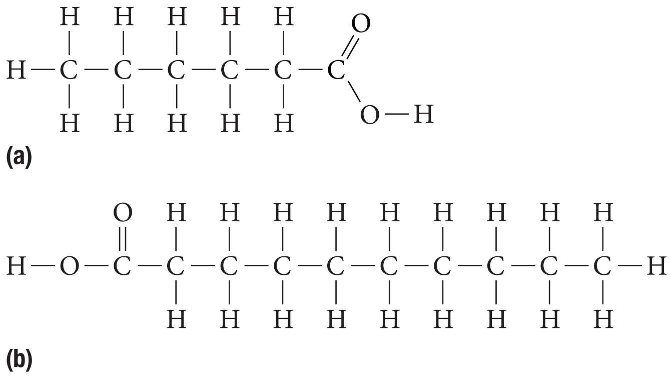


Figure 8

67. Suppose that your lab partner is having difficulty with the concept illustrated in **Figure 9**. How would you teach this concept to your lab partner? (3.4) K/U T/I C

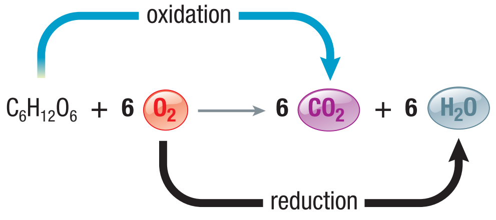


Figure 9

68. Draw two graphs to illustrate the energy changes that occur during the rapid combustion (burning) of glucose and the controlled oxidation of glucose in cellular respiration. How does the controlled oxidation of glucose benefit a cell? (3.4) K/U T/I C

69. A long-distance triathlete uses 28 000 kJ of energy during an 8 h race. (4.2) K/U T/I A
    (a) What mass of glucose is needed for the race? Assume that the intracellular conversion from glucose to ATP is approximately 40 % efficient, and that one mole of glucose yields 2870 kJ of energy.
    (b) Could the athlete consume this much glucose immediately prior to the race? Explain.

70. The air we breathe in is 21 % oxygen and 0.04 % carbon dioxide. However, the air we exhale is roughly 16 % oxygen and 5 % carbon dioxide. Use your knowledge of respiration to explain these observations. (4.2) K/U T/I

71. Brown adipose tissue has significantly more mitochondria than normal adipose tissue. (4.2) T/I
    (a) Why do some animals have a larger abundance of brown adipose tissue than other animals?
    (b) Where in the body would you expect to find brown adipose tissue? Explain.
    (c) Explain how the electron transport chain in the mitochondria in brown adipose tissue can be used for thermogenesis.

72. Copy **Table 1** into your notebook and complete it by entering the number of ATP molecules that are associated with each pathway. (4.2) K/U

Table 1

Pathway (per glucose molecule)	ATP produced through substrate-level phosphorylation	Associated ATP produced later, through oxidative phosphorylation	Total ATP
glycolysis			
pyruvate oxidation			
citric acid cycle			
Total			

73. Cyanide inhibits cytochrome oxidase C. (4.2) K/U T/I
    (a) Based on this information, explain why cyanide is toxic to humans.
    (b) Which tissues do you think would be most affected if you ingested a sub-lethal dose of cyanide? Explain your hypothesis.

74. Develop a graphic organizer that compares aerobic respiration to anaerobic respiration, based on the following criteria: (4.2) K/U T/I C
    - oxygen requirement(s)
    - location within a eukaryotic cell
    - amount of ATP produced per glucose molecule

75. A human can survive without oxygen for a few minutes, without water for a few days, and without food for several weeks. Use your understanding of cellular respiration to explain why. (4.3) K/U T/I

76. Predict whether a migratory bird would store energy as fats or as carbohydrates. Explain your reasoning. (4.3) K/U T/I

77. In this unit, you read about feedback inhibition in cellular respiration. You were given an example of ATP and citrate (two of the products of cellular respiration) inhibiting the enzyme phosphofructokinase, thus slowing down glycolysis. Give an example of feedback inhibition that might occur in your home. (4.3) K/U T/I A

78. Many people believe that forests are net producers of oxygen. However, for net production of oxygen gas to occur, photosynthesis must be occurring faster than cellular respiration. The following equations summarize the overall reactions of photosynthesis and respiration:

$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$

$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$

   (a) If there were a net production of oxygen gas in an ecosystem, what chemical would you also expect to accumulate in the ecosystem? Explain.
   (b) Predict how a net production of oxygen gas in an ecosystem would affect the total biomass of the ecosystem over time.
   (c) If the rate of photosynthesis were reduced on a global scale, what impact might this have on climate change? (4.4) K/U T/I A

79. Consider the analogy that plants and photovoltaic cells are similar in that they both capture and transform energy from the Sun by "exciting" electrons. If this analogy is true, why are photovoltaic cells black in colour, while plants are not? Defend your answer, and include a discussion about absorbed energy. (5.1) T/I C

80. Imagine that you are an electron in P680. Write a brief story, describing your trip through the light reactions of photosynthesis. (5.2) K/U C

81. Compare and contrast the chemical pathways of the C_4 cycle and the Calvin cycle. Include reactants, products, and energy consumption. (5.4) K/U T/I

82. Develop a flow chart that would help you determine the method of carbon fixation (C_3, C_4, or CAM) of any plant, based on the environment that you found it in. (5.4) K/U T/I C

83. Using what you know about the second law of thermodynamics, develop a hypothesis about whether life on Earth could survive without energy from the Sun. Support your hypothesis with evidence from Unit 2. (3.1, 5.1) K/U T/I

Evaluation

84. Compare how a car uses gasoline with how your body uses food. (3.1) K/U T/I

85. In humans, both the egg and the sperm contain mitochondria. Which of the two do you think contains the higher concentration of mitochondria? Justify your answer. (3.2) K/U T/I

86. If ATP is the energy currency of the cell, what analogy would you use to describe a carbohydrate molecule? (3.2) K/U T/I A

87. There are both benefits and risks associated with genetic engineering. One possible application involves modifying the genes that produce enzymes, such as the enzymes involved in lipid metabolism. (3.4) K/U T/I
   (a) What would be the benefits and risks associated with modifying the genes that produce the enzymes involved in lipid metabolism?
   (b) Would you recommend a treatment in which increased enzymatic lipid catabolism in cells was increased? Explain your reasoning.

88. Rolf Luft, a Swedish doctor, has a patient who has the following symptoms: heavy and continual perspiration, flushed skin, and weakness despite a large appetite. Dr. Luft suspects a metabolic disorder. Explain his diagnosis. (4.0) K/U T/I

89. Some metabolic disorders cause the ionophore channels across the mitochondrial membrane to leak. What impact would this have on the normal functioning of the body? (4.1) K/U T/I

90. The great architect Louis Sullivan made the following comment: "Form ever follows function. This is the law." Explain how this comment applies to mitochondria. (4.1) K/U T/I

91. A *homunculus* is a scale model of the human body. A homunculus can be based on the principle that the size of an organ is proportional to the number of nerve endings. Explain how **Figure 10** would appear if you re-drew it using the principle that the size of an organ is proportional to the number of mitochondria, rather than the number of nerve endings. Defend your explanation, and include a sketch in your answer. (4.1) K/U T/I C

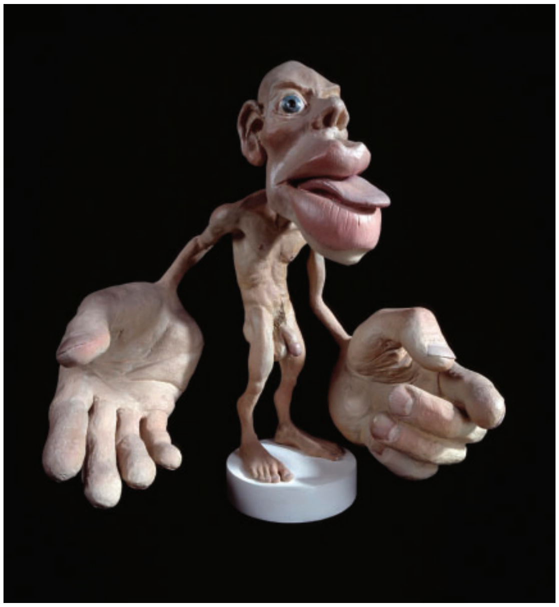


Figure 10

92. The advertisements for some supplements that contain pyruvate claim that the supplements can increase muscle endurance. Can you suggest why they make this claim? How could you evaluate this claim? (4.2) T/I A

93. If you modified the sequence of the protein complexes that make up the electron transport chain, would the electron transport chain still generate ATP? Explain your reasoning. (4.2) K/U T/I

94. Some marathon runners have found that taking short walking breaks during a race can sometimes help to improve their finish time. Other runners prefer to slow down their pace during portions of the race. If you ran a marathon, which of these techniques would you use? Defend your choice. (4.4) K/U T/I A

95. A group of students read, in a textbook, that plants use light as their primary source of energy. To test this, the students decide to conduct an experiment. They place 10 plants in total darkness and 10 plants in natural light, and then monitor the health of the plants over the next few weeks. To their surprise, many of the plants that were placed in total darkness survived for days and even weeks. However, the plants that were placed in the light appeared to be healthier. Was the textbook wrong? Account for the students' findings in your answer. (5.1) K/U T/I

96. While working at a Canadian space agency, you are asked to select a plant that could be transported to a space station. The agency would like to develop an environmental system using plants from Earth. (5.4) K/U T/I A
    (a) Develop a decision matrix that you could use to evaluate your decision.
    (b) Would you select a C_3, C_4, or CAM plant? Justify your reasoning.
    (c) The agency has now asked you to identify plants that could be used to generate oxygen on the space station. Which plants would you recommend, and why?

97. A scientist designs an experiment to examine the effect of light intensity on the Calvin cycle. As part of the experimental design, the scientist plans to measure the amount of glyceraldehyde-3-phosphate (G3P) that is produced at various light intensities. What do you expect would happen to the amount of G3P as the light intensity is increased? (5.4) K/U

98. For many years, scientists believed that C_4 plants evolved when the CO_2 level in Earth's atmosphere dropped during the Oligocene epoch. However, new evidence shows that C_4 plants existed before the CO_2 level dropped. What other environmental changes might have favoured the evolution of a C_4 pathway? (5.4) K/U T/I A

Reflect on Your Learning

99. After studying this unit, what information has most changed your understanding of how your body creates and uses energy from food? K/U T/I A

100. Describe your current understanding of the relationship between photosynthesis and cellular respiration. K/U T/I

101. Construct a mind map to show how you have linked the major concepts in this unit. K/U T/I C

102. How has this unit changed your understanding of the potential effects of climate change on photosynthetic organisms? K/U T/I A

103. List two careers or industries that you would like to learn more about after studying this unit. Explain why these careers or industries interest you. T/I A

Research

WEB LINK

104. Kleptoplasty is a symbiotic phenomenon in which plastids from one organism are taken by another organism with a completely different cellular environment. T/I
    (a) Use the Internet to research kleptoplasty. Write a brief summary about how this phenomenon occurs in nature, using specific examples.
    (b) What are some of the advantages and disadvantages of kleptoplasty for the organisms involved?
    (c) Are there any situations in which you think the human species could benefit from kleptoplasty?

105. Two scientists are in the running for a Nobel Prize in Chemistry. The first scientist discovered how photosystems work, and the second scientist discovered how chemiosmosis works. Imagine that you are a news reporter who has been asked to write an article about the achievements of both scientists. Conduct online research to learn about the scientists who were responsible for these discoveries, and draft your article based on the following criteria:
    - What has each scientist contributed to science?
    - What is the impact of their discoveries on society?
    - Who do you think most deserves the Nobel Prize? Explain your reasoning. K/U T/I C A

106. Use the Internet to research retinal. T/I A
    (a) Describe the biological function(s) of retinal.
    (b) How do animals obtain retinal?
    (c) Given its function(s), are you surprised that retinal is synthesized from a photosensitive pigment? Explain your answer.
    (d) In what other ways are plant-derived photopigments used by vertebrates?
    (e) Identify one photopigment that is synthesized by vertebrates. How is this photopigment synthesized and used?

107. Wastewater treatment is important to the well-being of the environment. Treating wastewater is expensive, however, so engineers often choose to use one or more types of micro-organisms to help process the sewage. Using the Internet, investigate the use of micro-organisms to treat sewage. Then answer the following questions. T/I
  (a) Why are microbes preferred to chemical treatment?
  (b) What are the most common microbes that are used? Are these microbes aerobic or anaerobic?
  (c) What are the costs and/or benefits to the environment?
  (d) In what other ways might micro-organisms be useful in industry in the future? Justify your answer.

108. Not all autotrophs rely on sunlight to synthesize the organic compounds they need for survival. Use the Internet to research chemoautotrophs, and then answer the following questions. T/I A
  (a) What kinds of organisms are chemoautotrophs? Where do they live?
  (b) How do chemoautotrophs compare with photosynthetic organisms (photoautotrophs), in terms of their primary source of energy and their sources of inorganic carbon?
  (c) Water is oxidized by photosynthetic organisms to supply hydrogen. What compounds are oxidized by chemoautotrophs to supply hydrogen?
  (d) In photosynthesis, light energy is used to form the key oxidizing agents $P680^+$ and $P700^+$. What are the key oxidizing agents that are used by chemoautotrophs? Is there any outside source of energy involved in their formation?

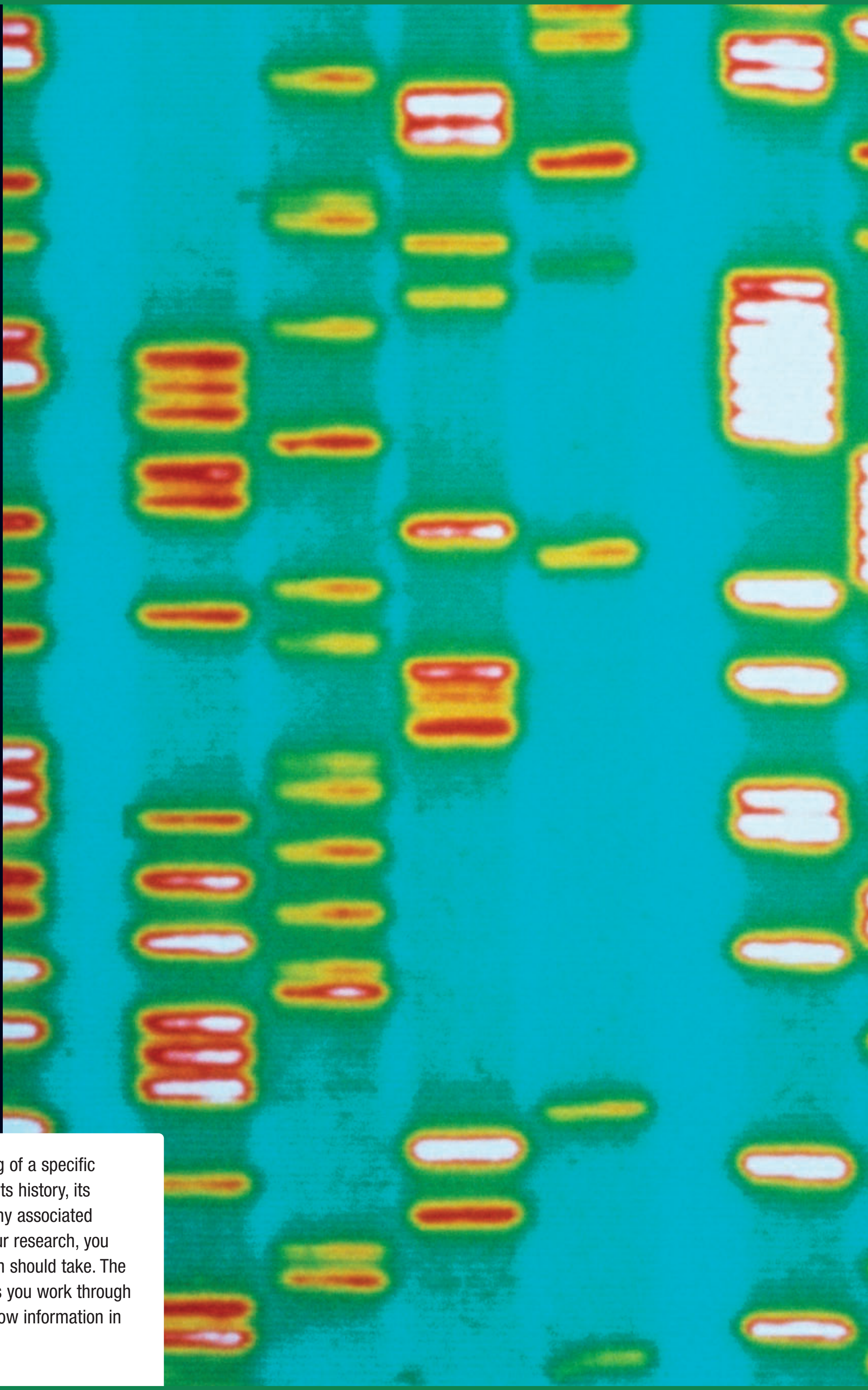
109. A fellow student asks you if it is true that all plants are photosynthetic and all animals are non-photosynthetic. Use the Internet to investigate the ecological relationships between
  (i) coral and zooxanthellae
  (ii) green sea slugs and algae
  (iii) saprophytic plants in general and one specific saprophytic plant, the Australian orchid *Rhizanthella gardneri* T/I A
  (a) What answer should you provide to your fellow student?
  (b) How did your research affect your appreciation for the diversity of life?

110. There are many opponents to the commercial production of ethanol using corn starch. Imagine that you are a government official who liaises with both the Ministry of the Environment and the Ministry of Industry. You have been asked to prepare a one-page brief about ethanol production for both ministries. T/I C
  (a) Conduct research on this controversial issue, and use your findings to prepare your brief. Make sure that you include the following information:
    - the status of Canada's current methods of ethanol production from starch
    - the advantages and disadvantages of the current methods (including costs), as well as their specific impacts on the environment and industry
    - a description of cellulosic ethanol production and an explanation of how it compares to ethanol production from corn starch
    - the impact of each method of ethanol production on industry and on the environment
    - your recommendation for which method of ethanol production the government should approve
  (b) Does your recommendation benefit one ministry more than the other? Explain.

111. Scientists with expertise in metabolic processes and genetics are experimenting with new techniques for treating cancer. They are using harmless anaerobic soil bacteria, *Clostridium sporogenes*, to target and kill tumour cells. They inject bacterial spores into the body. These spores can only grow and survive where oxygen levels are low—in this case, at the centre of solid tumours. The scientists then inject a drug that is activated by the bacteria. Use your own understanding of metabolic processes, as well as Internet research, to answer the following questions. T/I A
  (a) Why might the centre of a tumour be low in oxygen?
  (b) How is the drug activated by the bacteria?
  (c) How are the bacteria genetically altered to enhance their ability to activate the drug?
  (d) What is the current status of this technique? Is it being used to treat humans, or is it still being tested?
  (e) In what prestigious science journal did the scientists first publish their findings?

UNIT 3

Molecular Genetics



OVERALL EXPECTATIONS

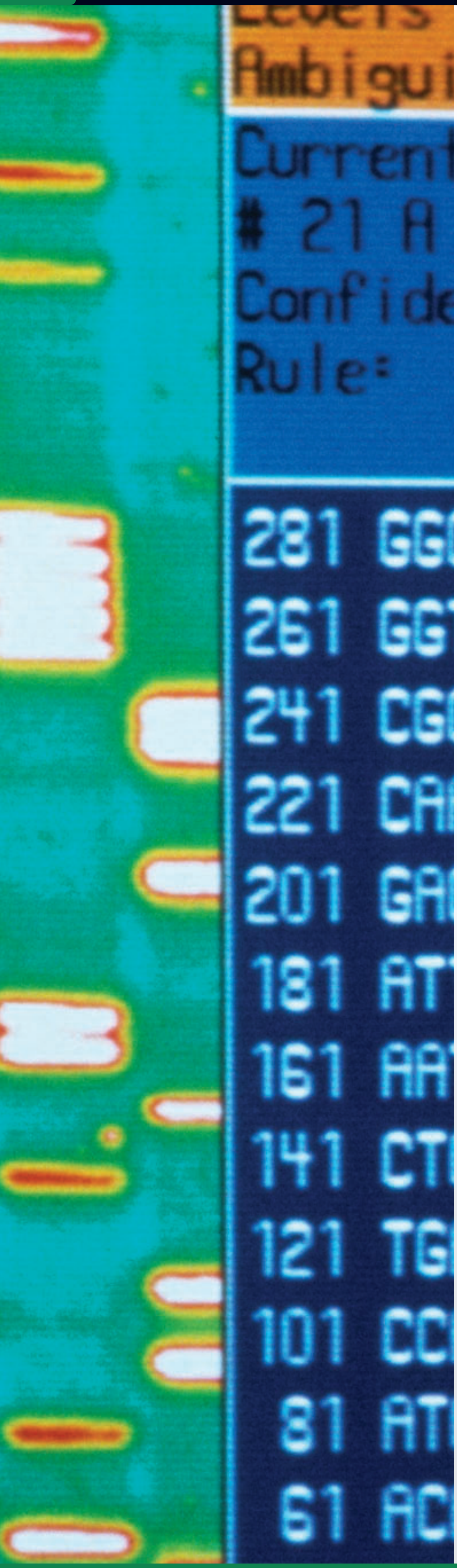
- analyze some of the social, ethical, and legal issues associated with genetic research and biotechnology
- investigate, through laboratory activities, the structures of cell components and their roles in the processes that occur within the cell
- demonstrate an understanding of concepts related to molecular genetics, and how genetic modification is applied in industry and agriculture

BIG IDEAS

- DNA contains all the genetic information for any living organism.
- Proteins control a wide variety of cellular processes.
- Genetic research and biotechnology have social, legal, and ethical implications.

UNIT TASK **PREVIEW**

In this Unit Task, you will gain an understanding of a specific application of biotechnology. You will research its history, its current and possible future applications, and any associated ethical or societal considerations. Based on your research, you will decide which direction (if any) this research should take. The Unit Task is described in detail on page 410. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.



SEQUENCING OUR PAST, UNDERSTANDING OUR FUTURE

In 2001, a monumental scientific feat was accomplished. For the first time in the history of life, an organism had figured out how to read its own instruction manual. The sequencing of the human genome was the result of years of research, conducted by thousands of scientists around the world. Since then, researchers have made huge advances in sequencing the genomes of other species, discovering the locations of specific genes and using this knowledge to build proteins in other organisms. (For example, insulin can now be grown in safflower plants and bacteria.) Using the genetic code and new technologies, scientists have been able to determine the evolutionary background of many species, develop crops that can be grown with fewer herbicides, and even treat certain diseases. They are applying their new genetic knowledge to questions from all fields of biological science, as well as raising new questions to be investigated in the future.

While some researchers are sequencing the genomes of species such as mice and fruit flies, others are attempting to sequence the genome of our closest extinct relative, the Neanderthal. This is not an easy task, since fossils can be contaminated by bacteria and human handling. However, advanced techniques in DNA replication have allowed researchers to compare our own genome with that of our ancestors. One significant result of their work has been the discovery of the *FOXP2* gene, present in all mammals. In modern-day humans, it plays an important role in speech development. A *FOXP2* gene, identical to the version in humans, has been found in Neanderthals, suggesting that language has been around for much longer than we originally thought. These and similar studies hold the keys to discovering which genes contributed to the development of human civilization.

Another exciting field is proteomics and transcriptomics. Just as genomics is the study of the genome, proteomics is the study of the entire set of proteins that a genome can produce. Since proteins are the building blocks of an organism and play a huge role in cellular functioning, knowledge of their structures, functions, and interactions may lead to new therapies for countless conditions. Transcriptomics is the study of a genome's rate of expression. Discoveries in this field may lead to new methods of diagnosing diseases.

Questions

1. How many genes do you think are in the entire genome of each of the following organisms? Justify your thinking.
   (a) human
   (b) salmon
   (c) fruit fly
   (d) maple tree
2. Describe a recent news story about a discovery related to genetics.
3. Some people suggest that a person's genomic information should be provided to insurance companies. How could the genomic information be used? How could it be abused? How do you feel about this?
4. Using your current knowledge of genetics, make a list of some of the genes that all life forms may share.

UNIT 3 ARE YOU READY?

CONCEPTS

- differentiate between mitosis and meiosis
- identify the structure and function of cell organelles
- explain the importance of deoxyribonucleic acid (DNA)
- understand hydrogen bonding
- distinguish between alleles, genes, and chromosomes
- understand genetic mutations

SKILLS

- develop and interpret graphs and diagrams
- distinguish between reputable and non-reputable sources of information
- analyze social and ethical issues related to biotechnology
- communicate using written and verbal format
- define scientific terms, and use them in context

Concepts Review

1. What is DNA, and what is its function in life? K/U
2. Describe the structure of DNA. What are the key components of a DNA molecule? K/U
3. (a) Where in the cell is DNA found in eukaryotes?
   (b) Where is DNA found in prokaryotes? K/U
4. Is the DNA code in a liver cell different from the DNA code in a muscle cell? Explain. K/U
5. During which part of the cell cycle does DNA replicate? K/U
6. Why is it important for DNA replication to occur accurately during cell division? K/U
7. Why does each cell have two copies of each DNA molecule? K/U
8. (a) What is a chromosome?
   (b) What is chromatin?
   (c) How do chromosomes and chromatin differ, and when are they present during the cell cycle? K/U
9. Describe the differences between mitosis and meiosis in terms of the end result. K/U C
10. What is a hydrogen bond? Give an example. K/U
11. (a) What is a genetic mutation?
    (b) Are all mutations considered to be negative?
    (c) Provide an example of a mutation. K/U
12. The following sequence represents one strand of a DNA molecule: ATAGGCATCCA
    Using your knowledge of base pairs, write out the complementary strand of DNA. K/U T/I
13. In one sentence, describe the relationship between genes, alleles, and chromosomes. K/U C
14. Use a Venn diagram to compare and contrast somatic and germ cells in humans. K/U C

Skills Review

15. An experiment was conducted to determine the mutation frequency in bacteria exposed to a certain chemical. Scientists found that each test tube contained 10^7 bacterial cells, with an average of 12 mutations. Calculate the mutation frequency in the bacteria. T/I
16. In the early 1970s, scientists conducted an experiment to determine the DNA, RNA, and protein content in the nuclei of pea seedlings. After extracting the nuclei, they found that the dry mass of an average pea nucleus was 53.0 pg (picograms). They also found that the DNA had a dry mass of 10.5 pg, the RNA had a dry mass of 3.4 pg, and the protein content had a dry mass of 33.6 pg. T/I
    (a) What percentage, by mass, of a nucleus is composed of DNA? What percentage is composed of RNA? What percentage is composed of protein?
    (b) Calculate the mass ratio of DNA : RNA : protein in a pea seedling nucleus.
    (c) Calculate the mass of DNA that would be found in 10 g of pea nuclei.
    (d) Assume that the DNA content of a pea seedling nucleus is actually 15.0 pg. Calculate the percentage yield that these scientists obtained.
    (e) In a different experiment, only 9.0 pg of DNA was extracted from a pea seedling nucleus. Calculate the percentage error for this experiment.
17. At various times during this unit, you will be asked to conduct research on the Internet.
    (a) What criteria will you use to determine whether a website is reputable?
    (b) What techniques will you use to find reputable websites? T/I
18. Biotechnology is the use of biological organisms or processes for industrial or commercial purposes. What criteria would you use to analyze the social and ethical issues related to new biotechnologies? T/I

19. To maximize the isolation of DNA from onions, the following experiment was conducted. SDS (sodium dodecyl sulfate) is a detergent that breaks up the cell and nuclear membranes, liberating their contents, including their DNA. T/I

- Treatment 1: onion cells treated with 10 % SDS
- Treatment 2: onion cells treated with 15 % SDS
- Treatment 3: onion cells treated with 20 % SDS
- Treatment 4: onion cells treated with no SDS

(a) What were the independent and dependent variables in this experiment?
(b) Was a control used in this experiment? If so, what was the control?
(c) If you graphed the data obtained in this experiment, what variable would you put on the *x*-axis? What variable would you put on the *y*-axis?

20. Look at the following two micrographs of endoplasmic reticulum (**Figures 1** and **2**). Which micrograph represents rough endoplasmic reticulum? How can you tell? K/U T/I

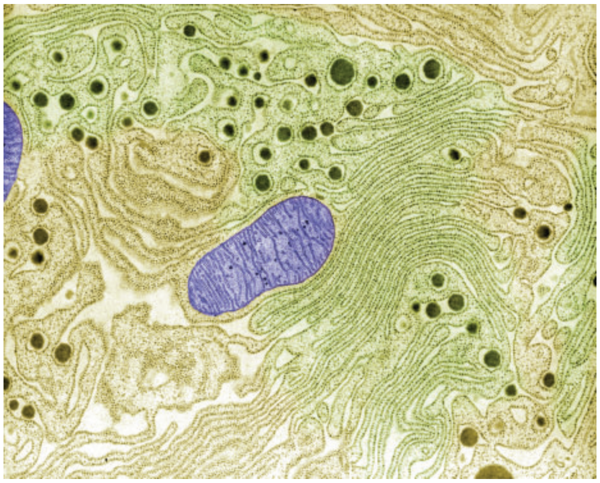


Figure 1

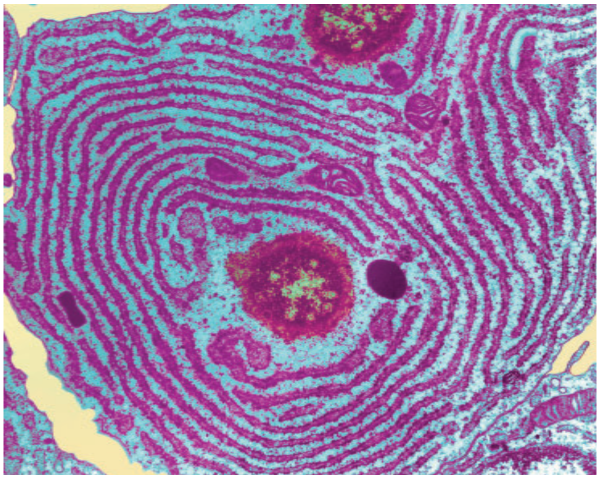


Figure 2

21. When DNA replicates, it makes a perfect copy of itself. An error in this process may be a mutation. A mutation is any change in the DNA sequence. Some mutations are harmless, and some may even be helpful. However, others may cause structural or functional difficulties for an organism. The data in **Table 1** is from an experiment that measured the rate of replication errors, given an organism's age. T/I C

Table 1

Age of organism (years)	Errors per one million replications
5	10
10	15
20	20
35	45
55	60
75	1000

(a) Graph the data.
(b) Describe any trends that you observe.
(c) What are the independent and dependent variables?
(d) How could a mutation contribute negatively to the well-being of an organism? How could it contribute positively?

22. Draw and label a simple diagram of the cell cycle. Include labels for interphase, mitosis, and cytokinesis. K/U C

CAREER PATHWAYS PREVIEW

Throughout this unit you will see Career Links. Go to the Nelson Science website to find information about careers related to molecular genetics. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 6

DNA: Hereditary Molecules of Life

KEY CONCEPTS

After completing this chapter you will be able to

- describe how DNA (deoxyribonucleic acid) carries the hereditary information for living organisms
- explain how the discovery of DNA occurred in a series of experiments over a number of years
- describe the structure of DNA as a double helix molecule, with complementary bases that replicate themselves semiconservatively
- explain how DNA replication is checked and edited by enzymes to avoid errors
- describe how DNA is organized in different ways in prokaryotes and eukaryotes

How Does DNA Replicate Itself?

At this moment, inside your body, millions of cells are dividing. Cell division ensures growth, as well as the repair and replacement of worn or damaged tissues. It is an absolute necessity for our survival and well-being. For example, skin cells form a vital protective layer that is constantly being replaced as the dead cells on the surface wear away. Red blood cells have a lifespan of between 100 and 120 days. Although they do not divide by themselves, they are produced in specialized tissues of our bone marrow at an amazing rate of about 200 billion new cells every day. Other cells rarely divide. For example, neurons in the brain and throughout the body rarely divide or replace themselves, and then only under special circumstances.

Every time a cell divides, an exact copy of its genetic information must be passed on to each of the two new cells produced. This is a huge task. Copies of molecules that consist of 6 billion base pairs (the diploid set) must be made, and each base pair must be "matched." At the rate of one base per second, this would take 190 years. However, our cells can do it in minutes—with an error rate of less than one in a million! How is that possible?

All cells—animal cells, plant cells, fungus cells, protists, archaea, and bacteria—use molecules of deoxyribonucleic acid (DNA) to carry information. Each daughter cell must be genetically identical to its parent cell, so DNA replication (copying) must be accurate. If the DNA is damaged or altered (mutated), the new cells may not function in the same manner as the parent cells did. DNA mutations do occur, but DNA repair mechanisms operating during replication keep mutation levels extremely low.

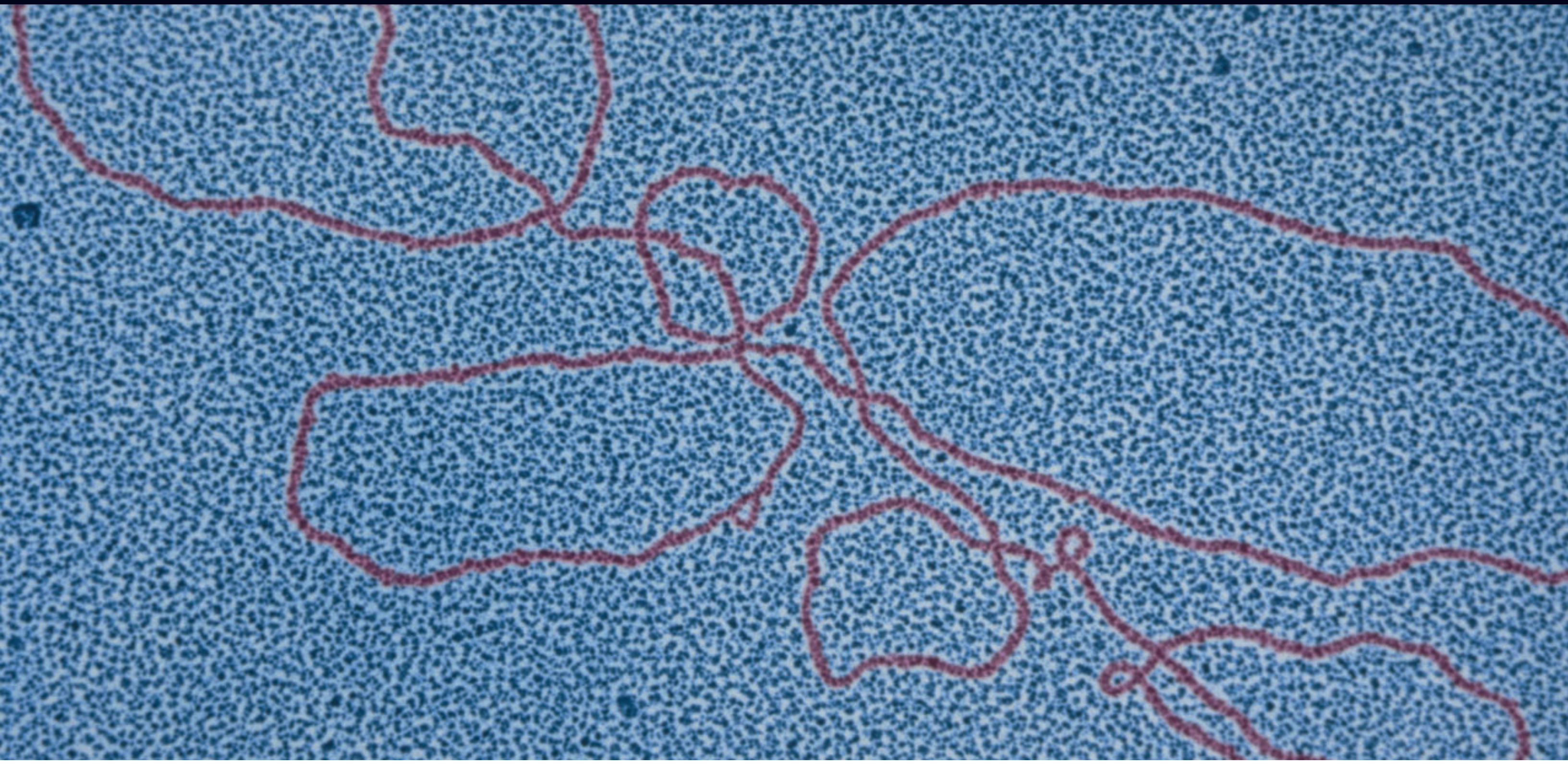
In this chapter, you will learn how DNA is able to replicate itself. The double helix structure of DNA has an integral role in this. The base sequences on each strand of the helix are complementary to each other. As you will learn, the structure of DNA dictates the way that DNA is replicated.

The determination of the structure of DNA in 1953 was arguably the most important event in biology in the twentieth century. James Watson and Francis Crick used the information accumulated over a century of experimentation and research to describe its elusive structure. Throughout this chapter, you will learn about the men and women whose insights and experiments built the foundations for Watson and Crick's findings and established the basis for all our present-day knowledge of DNA structure and function.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. When, where, and how often is DNA copied? Explain your answer.
2. How might the structure of DNA lend itself to being rapidly and accurately copied?
3. Based on what you have learned about biochemistry and metabolic processes in Units 1 and 2, speculate on the role of enzymes and ATP in DNA replication and repair.
4. Books, like DNA, contain valuable information. The front and back covers of a book protect it from being damaged by everyday use. Speculate on how cells might protect their DNA. Could DNA have protective "ends"?



Mini Investigation

Build a DNA Model

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1**

The genetic code in DNA is represented with four letters that represent the nitrogenous bases: adenine (A), thymine (T), cytosine (C), and guanine (G). The bases are complementary, meaning that each base exclusively pairs with one base. Adenine on one strand always pairs with thymine on the complementary strand, and cytosine always pairs with guanine. In this activity, you will build a model of a DNA molecule using different-coloured beads to represent the nitrogenous bases.

Equipment and Materials: bag of 25 plastic beads of four different colours; bag of 50 plastic beads of four different colours; 2 pieces of string (each about 2 m long)

1. Assign each colour of bead to one of the four nitrogenous bases in DNA: A, T, C, and G. Tie a knot in one end of a piece of string. In random order, string the 25 beads from the first bag on this first string. Record the letter code represented by the beads.
2. Write down the complementary code. String the second piece of string with the 25 beads from the bag of 50 beads that represent the complementary code.
3. Hold both strings at both ends, making sure that the complementary beads are touching. Gently twist the two strands together. Observe.

A. What does the twisting of the strings represent? Does the direction that you twist the strands affect the accuracy of your model? Explain. T/I

B. How well does this final arrangement model a DNA molecule? Explain your thinking. T/I

C. DNA strands are held together by hydrogen bonding between the complementary base pairs. How could your structure be changed to model this bonding? T/I

D. What property of a DNA molecule might play a role in making accurate copies of old strands during replication? (Think about creating your second string.) T/I

E. Consider a single human gene that is 10 000 base pairs long. Based on the length of your 50-bead double strand, calculate the length of a bead model of this gene. T/I

F. Considering how long you took to copy 25 base pairs in this activity, how long would you need to copy the single human gene in Part E? Do the same calculation for an entire chromosome, with 50 million base pairs. T/I

6.1 The Molecular Basis of Inheritance

DNA (deoxyribonucleic acid) is the primary carrier of genetic information in all living organisms on Earth. From the simplest bacterium to the most complex animal, all organisms use DNA to pass information for their construction and operation from one generation to the next. Within an organism's DNA are the instructions necessary to build all the proteins it requires. DNA is responsible for ensuring the genetic continuity of the species, and therefore the continuity of life.

DNA is passed from generation to generation in the form of chromosomes. In eukaryotes, chromosomes may be visible in the cells during cell division. They appear as the familiar X-shaped objects that are split during mitosis or meiosis. The size and number of chromosomes in a cell are specific to each species. Humans, for example, have 46 chromosomes in each body cell, turkeys have 82, fruit flies have 8, sea stars have 36, and potatoes have 48. Most bacteria have only a single chromosome, while some plants contain many hundreds of chromosomes in each cell. The adder's tongue fern has the largest known number—about 1200. Following cell division, the chromosomes unravel to their functional form and spread throughout the new nucleus. They are no longer visible without powerful magnification.

Composed of amino acids, proteins are found throughout an organism. Some proteins are common to all forms of life, while others are specific to an individual species. Proteins have many roles, both physical and chemical. For example, proteins that are enzymes have the vital function of catalyzing all cellular reactions. When a particular protein is needed, the portion of DNA (the gene) that codes for this protein is activated. The nucleotide sequence is copied (transcribed) into a molecule of RNA (ribonucleic acid). The RNA then moves to the cytosol, where its sequence is translated by the ribosomes into amino acid chains called polypeptides. Elsewhere in the cell, polypeptides are further modified to form functional proteins. The entire process of protein synthesis will be covered in depth in Chapter 7.

Heredity and DNA

Our understanding of genes and the role of DNA in inheritance started with the simple experiments of an Austrian monk, Gregor Mendel. He spent his spare time breeding the pea plant *Pisum sativum*. Mendel developed techniques to pollinate selected flowers with the pollen from other selected flowers (**Figure 1**). Over seven years in the late 1800s, he statistically analyzed the inherited characteristics of over 28 000 plants. His analysis clearly showed how certain traits were expressed in the next generation from each cross-pollination experiment. He proposed that factors for a given trait were passed from parent to offspring, although at the time, he had no idea of how this actually happened. Because of the work that Mendel began, we now know that a hereditary molecule does exist. Over the past 100 years, numerous experiments, using increasingly sophisticated methods, have revealed that DNA is the carrier of the hereditary information.

Figure 1 Researchers still use Mendel's hand pollination techniques to crossbreed plants such as this strawberry.

All new cells arise from the division of existing cells, and all the information that is needed for optimal cell functioning is coded in a cell's DNA. In eukaryotes, the DNA is stored in the nucleus. In prokaryotes, it is stored in the cytosol. Regardless of the location, all forms of life use DNA in the same way to build proteins and grow new cells. How the message in DNA is decoded to make proteins is central to the development of all life.

Genes and Chromosomes

During his experiments, Mendel proposed a "factor" for each specific trait that is inherited by an organism. All the inherited and measurable characteristics of an organism, including its size, colour, and markings, are the result of these factors being passed from parents to offspring and expressed in the new organism. Today, we know that these factors are derived from our genes. Genes are the coding regions of DNA, which contain the instructions for building the proteins that are responsible for each inherited trait (**Figure 2**). In fact, there are several versions of each gene, called alleles, that give a trait more than one potential physical appearance. For example, different alleles of a certain gene give rise to round eyes or almond-shaped eyes, which are just two of the many alleles for the eye-shape characteristic.

Genes are scattered along an organism's DNA strands and can vary greatly in length. Within a species, the gene for a particular characteristic is always found in the same location on a particular chromosome. As scientists continue to study the genetic makeup of a great variety of organisms, they are discovering that many fundamental genes (such as those that direct the development of an embryo or the building of cell membranes) are shared by almost every form of life.

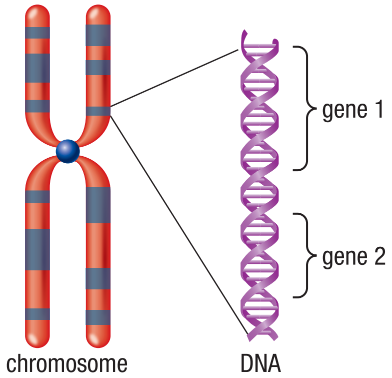


Figure 2 Genes make up the coding section of DNA. DNA strands are tightly coiled and compacted to form chromosomes, which are visible during cell division.

An enormous amount of information is stored in an organism's DNA, and it must fit inside every cell in the organism. Eukaryotes and prokaryotes handle this packing problem in different ways. In eukaryotes, the DNA is stored as chromosomes in the nucleus of each cell. In a eukaryotic chromosome, a DNA strand is wrapped around special proteins called **histones** to form a complex. Several of these complexes are bundled into coils to form thicker strands called chromatin fibres. This arrangement protects the DNA and reduces its volume so that it fits more easily into the nucleus. This DNA packing is discussed later, in Section 6.5. Eukaryotes also have very small amounts of DNA in their mitochondria and chloroplasts. The structure of this DNA is similar to the structure of the DNA found in prokaryotes.

histone a special protein molecule that is the core around which the DNA strand wraps

Archaea and bacteria do not have a membrane-bound nucleus, but they do have regions that are rich in DNA. Because these organisms are less complex, they contain less genetic material. Bacterial chromosomes are usually found in loops. The bacterial DNA is joined end to end to form one large ring. Smaller accessory loops of DNA, called **plasmids**, may also occur. Plasmids carry smaller amounts of genetic information—often only a few genes—and are sometimes copied and passed from one bacterium to another. The region of the cell that contains the looped DNA is called the nucleoid. Archaea also have circular chromosomes but, like eukaryotes, their DNA is associated with histone-like proteins. You will learn more about the organization of DNA in both eukaryotes and prokaryotes in Section 6.5.

plasmid a small circular section of DNA found in the cytosol of bacteria; replicates independently of the chromosomal DNA

The Genome

The entire complement of hereditary information that is contained in an organism is called its **genome**. The genome of a eukaryote is usually spread over many chromosomes, which often occur as pairs of homologous chromosomes. Each pair represents two copies of a particular set of genes. For example, humans have 23 homologous pairs of chromosomes of different sizes, two of which are special sex chromosomes (**Figure 3**). Each set of 23 chromosomes contains a total of more than 20 000 different genes, which are combined to form roughly 3 billion base pairs.

genome the complete set of an organism's hereditary information

Most eukaryotes are diploid (they have two sets of chromosomes), but there are many exceptions. Some large groups of species, such as bees, wasps, and ants, are haplodiploids. All the females are diploid, while all the males are haploid and contain only a single copy of each gene. Many plants are haploid, triploid, tetraploid, or even hexaploid. Different varieties of wheat, for example, have four or even six sets of chromosomes per cell.

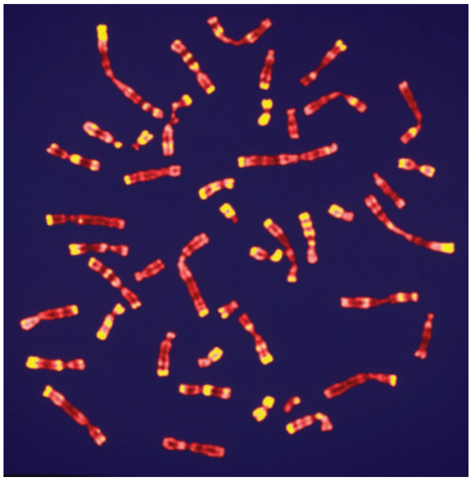


Figure 3 Micrograph of the human genome

6.1 Review

Summary

- DNA is the molecule that carries genetic information in all living things.
- A gene is a region of DNA that codes for the building of a particular polypeptide.
- Eukaryotic DNA is wound around histone proteins and organized into linear chromosomes. The chromosomes are found inside the nucleus of each cell.
- The genome of most eukaryotes is in the form of homologous sets of chromosomes in diploid organisms.
- Prokaryotic cells usually have a single chromosome, which is in the form of a loop of DNA and is not associated with histones. Most of the genome is stored in this chromosome, but smaller loops of DNA, called plasmids, may also be present.

Questions

1. Explain the difference between an allele and a gene. T/I
2. One base pair is about 3.3×10^{-10} m long. If the human genome contains roughly 3 billion base pairs, how long is our genome? T/I
3. Place the following terms in order of size, from smallest to largest: chromosome, genome, gene, nucleus. T/I
4. Differentiate between the following terms:
   (a) a factor (as described by Mendel) and an allele
   (b) a protein and a ribosome
   (c) DNA and a chromosome K/U
5. Create a concept map that includes the following terms: DNA, RNA, protein, nucleus, gene, allele. T/I C
6. Is there a difference between DNA in eukaryotes and DNA in prokaryotes? Explain. K/U
7. Species vary greatly in the number of chromosomes they possess. For example, the fruit fly has only eight chromosomes whereas the adder's tongue fern has about 1200 **(Figure 4)**. Using online resources, find the number of chromosomes in three different species. T/I
   (a) What might the number of chromosomes suggest about the complexity of the organism?
   (b) Could a species with a small number of chromosomes have a larger genome, or more genes, than a species with a large number of chromosomes? Explain.

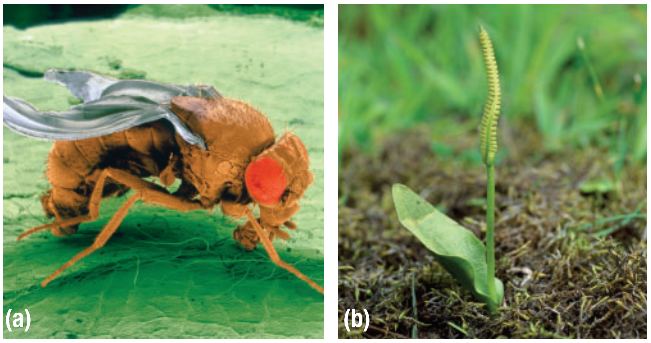


Figure 4 (a) fruit fly; (b) adder's tongue fern

WEB LINK

DNA Structure and Function: A History

About 150 years ago, Mendel hypothesized the existence of a hereditary molecule that passes genetic information through the generations. Less than 70 years ago, scientists determined that this hereditary material is, in fact, DNA. Scientists have now sequenced the genome of many species, including humans, important crop plants, disease-causing micro-organisms, commonly used research animals and plants, and close genetic relatives of humans, such as the chimpanzee. This information has enhanced our understanding of the role that genetic mutations play in diseases such as breast cancer, prostate cancer, muscular dystrophy, and cystic fibrosis. Currently, scientists are using this information to develop gene therapy technologies and trial vaccines that directly target the genetic mechanisms in viruses. CAREER LINK

Outside of medicine, DNA analysis has been used to determine the lineage of King Tutankhamun, an Egyptian pharaoh. Police investigators use DNA technology to help them solve crimes and convict criminals. Every day, scientists around the world discover more about how DNA guides the functioning and evolution of life on Earth.

These discoveries have been possible due to the accumulated findings of many scientists. A single researcher rarely makes a major discovery without input from other scientists. The nature of science is collaborative and cumulative. Many hard-working and dedicated people, over many years, have added their contributions to the pool of scientific knowledge. While some of these people receive praise, even awards such as the Nobel Prize, others remain virtually unknown. The story of the discovery of the structure and function of DNA—like any other scientific discovery—is filled with many interesting people and their research developments.

Establishing DNA as the Hereditary Molecule

In 1868, Swiss physician Frederick Meischer was interested in the composition of the cell nucleus (**Figure 1**). At the time, proteins were thought to be the hereditary material because they were known to be complex and carry out numerous biological functions. Meischer collected pus (mainly white blood cells) from the bandages of his patients. From these cells, he extracted large quantities of an unknown substance that was acidic and had a large amount of phosphorus. Not knowing the true nature of this substance, he named it "nuclein" because he found it in the nucleus of the white blood cells.

At the time of Meischer's discovery, scientists knew little about the molecules and processes that underlie heredity. Although Mendel was crossbreeding his peas at about the same time (1865), his work was generally unnoticed until the early 1900s. Many scientists believed that heredity involved a mixing of characteristics from the two parents. However, they could not explain why a short woman and a tall man produced children with a variety of heights, not a height that was an average of the two parents' heights. The chemical composition and function of Meischer's newly discovered molecule, nuclein, were not determined for more than 50 years, and its structure was not determined until some decades after that.

Figure 1 Frederick Meischer discovered "nuclein," later identified as DNA.

Frederick Griffith: The Transforming Principle

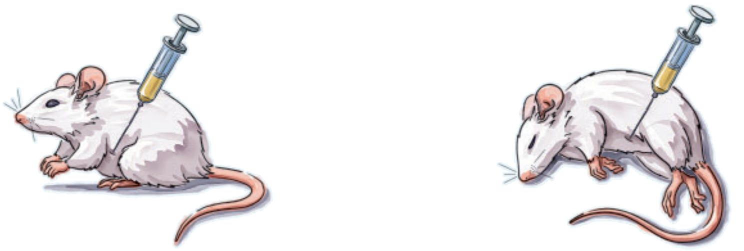
The role of Meischer's nuclein as the hereditary material was still unknown when, in the last days of World War I, a pneumonia epidemic struck Europe. Frederick Griffith, a medical officer for the British military, decided to research this disease. In 1928, he carried out an experiment that accidentally shed light on the function of DNA in inheritance.

Griffith used two different strains of the pneumonia bacterium. One strain had a capsule that surrounded each cell and caused the bacterial colonies to look smooth and glossy when grown on agar. Griffith called this the smooth strain, or S-strain, of pneumonia. The second strain of pneumonia lacked this smooth capsule and, as a result, formed rough and irregular colonies when cultured. He called this strain the rough strain, or R-strain. When Griffith injected mice with the S-strain, the mice contracted pneumonia and died in a matter of days. The S-strain bacteria were highly virulent (pathogenic) (**Figure 2(a)**). However, when Griffith injected mice with the R-strain of bacteria, the mice showed no signs of pneumonia and survived (**Figure 2(b)**). Griffith concluded that the capsule surrounding the S-strain was responsible for the virulence.

Griffith's next step was the important one. He heated the S-strain cells, destroying the capsule that surrounded the cells and killing the bacteria. The dead S-strain no longer caused an infection in the mice (**Figure 2(c)**). However, when he mixed the heat-killed S-strain with the live non-virulent R-strain, many of the mice contracted pneumonia and died (**Figure 2(d)**). Griffith then isolated living bacteria that appeared to be S-strain bacteria from the dead mice. Somehow, the living R-strain bacteria acquired some factor from the heat-killed S-strain that made them virulent. The newly virulent R-strain bacteria even formed smooth colonies when cultured, just like the living S-strain bacteria. We now know that bacteria can take up genetic material from nearby bacteria and use this DNA as their own.

(a) Mice injected with live S-strain cells died.

(b) Mice injected with live R-strain cells lived.



(c) Mice injected with heat-killed S-strain cells lived, showing that S-strain cells must be alive to be virulent to mice.

(d) Mice injected with heat-killed S-strain cells plus live R-strain cells died. Live R-strain cells were converted to virulent S-strain cells with some factor from dead S-strain cells.

Figure 2 Mixing heat-killed S-strain cells with live R-strain cells made the R-strain cells virulent.

Although Griffith could not identify the exact material involved in inheritance, he understood that some hereditary substance had passed from the dead S-strain cells to the live R-strain cells. When the R-strain bacteria acquired this material, they were effectively transformed into infectious S-strain bacteria. He called this process **transformation**, and he called the factor that was responsible the transforming principle. At the time, the most likely candidates for the transforming principle were proteins and DNA, but further experiments were required to determine its identity.

transformation a change in a genotype or phenotype caused by the direct uptake of genetic material by a cell

Avery, McLeod, and McCarty: DNA Transformation Confirmed

Building on Griffith's findings, physician Oswald Avery and his co-workers Colin McLeod and Maclyn McCarty carried out a series of similar experiments in 1944. The researchers grew different strains of *Streptococcus* bacteria in culture tubes that contained a growth medium. They kept the different strains isolated from one another. Like the pneumonia bacteria, *Streptococcus* have S- and R-strains, which differ in their disease-causing ability. Avery and his colleagues wanted to determine which part of the S-strain bacteria cell was responsible for making R-strain bacteria virulent. The possible transforming substances were DNA, RNA, and proteins. Like Griffiths, they heat-killed the S-strain. Then they treated molecules extracted from the dead bacteria with one of three enzymes to destroy one of the three possible transforming substances. They mixed each extract with R-strain bacteria and recorded how the new cultures looked when grown in culture tubes.

Although their results clearly showed that DNA was the transforming substance, Avery and his colleagues were hesitant to report this directly. At the time, most scientists believed that proteins were the genetic material. If some protein had not been destroyed by the enzymes, their results would be incorrect. Furthermore, precise experiments were required to establish the role of DNA as the carrier of genetic information.

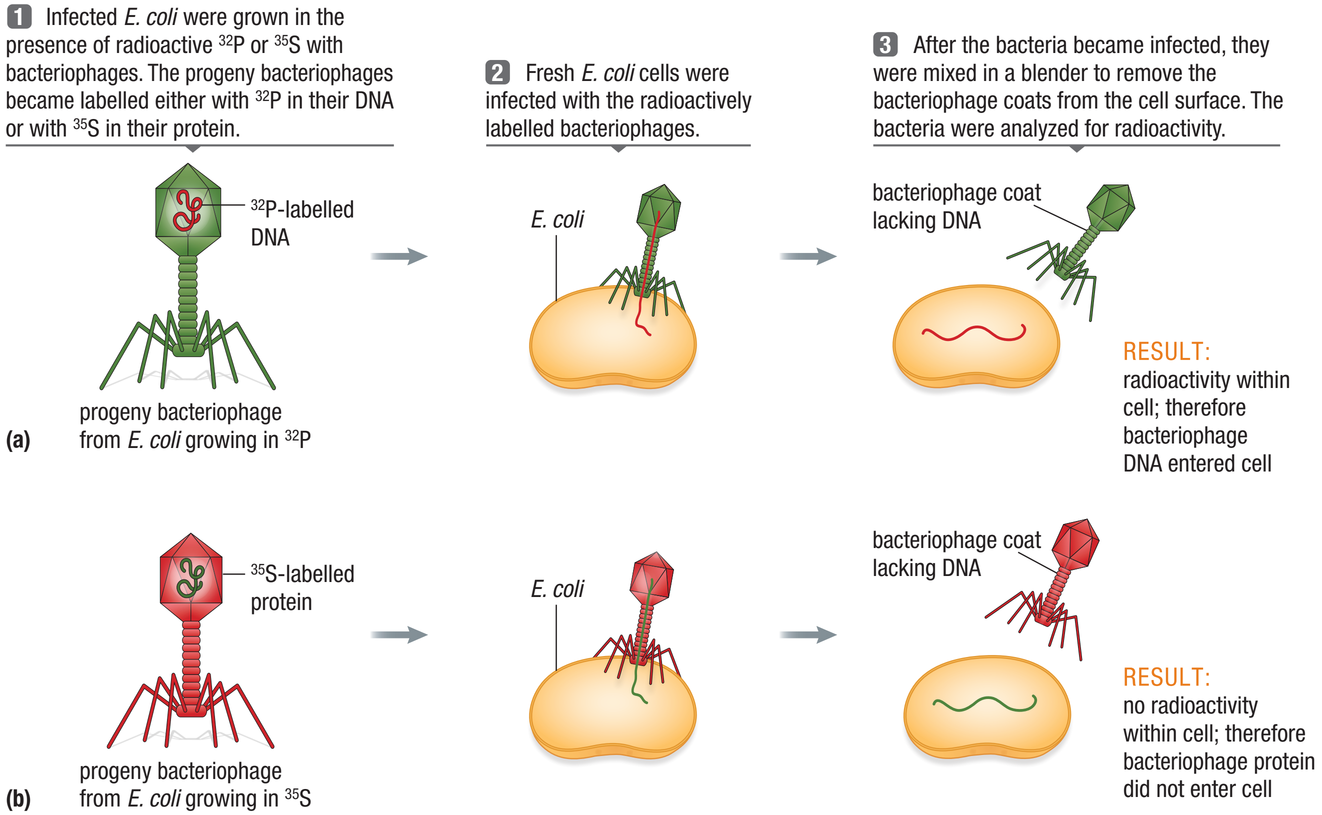
Hershey and Chase: DNA Is the Hereditary Material

In 1952, bacteriologists Alfred D. Hershey and Martha Chase attempted to determine whether proteins or DNA functioned as the genetic material. They used a virus and the bacteria *E. coli*. The virus they used was a **bacteriophage**: a virus that specifically infects bacteria. The particular bacteriophage they used had both DNA and a protein coat. When a bacteriophage infects a bacterium, it inserts its genetic material into the bacterium and uses the bacterium's cellular processes to produce new bacteriophages. Keep in mind that, at the time, no one knew what part or parts of a virus entered cells during an infection or even what a virus looked like. Viruses were much too small to be seen with the most powerful microscopes available. WEB LINK

bacteriophage a virus that infects bacteria

Hershey and Chase knew that bacteria could be transformed by viruses, but they did not know which part of the virus—the protein coat or the DNA (or RNA)—did the transforming. They used radioisotopes to label the different molecules. An isotope is an atom of an element that has a different number of neutrons than usual, and a radioisotope is an isotope that emits radiation.

Hershey and Chase used the radioisotopes of phosphorus and sulfur, ^{32}P and ^{35}S. Sulfur was used to label proteins because proteins contain sulfur but DNA molecules do not. Phosphorus was used to label DNA because DNA molecules contain phosphorus while proteins contain only a tiny amount. Hershey and Chase labelled some bacteriophages with the sulfur isotope and other bacteriophages with the phosphorus isotope, and then infected different colonies of the bacteria (**Figure 3**).



1 Infected *E. coli* were grown in the presence of radioactive ^{32}P or ^{35}S with bacteriophages. The progeny bacteriophages became labelled either with ^{32}P in their DNA or with ^{35}S in their protein.

2 Fresh *E. coli* cells were infected with the radioactively labelled bacteriophages.

3 After the bacteria became infected, they were mixed in a blender to remove the bacteriophage coats from the cell surface. The bacteria were analyzed for radioactivity.

RESULT: radioactivity within cell; therefore bacteriophage DNA entered cell

RESULT: no radioactivity within cell; therefore bacteriophage protein did not enter cell

(a)
32P-labelled DNA
progeny bacteriophage from E. coli growing in 32P
E. coli
bacteriophage coat lacking DNA
(b)
35S-labelled protein
progeny bacteriophage from E. coli growing in 35S
E. coli
bacteriophage coat lacking DNA

Figure 3 Hershey and Chase used progeny bacteriophages labelled with radioisotopes of either (a) phosphorus, ^{32}P, or (b) sulfur, ^{35}S. Their experiments indicated that DNA is the material transmitted from virus to bacteria.

After providing time for the bacteria to become infected, they separated the bacterial cells from any viral particles remaining outside the cell. Depending on which radioisotope they found within the bacterial cells, the true hereditary material would be found to be either DNA or protein. Their results were conclusive. Radioactivity was only detected within bacterial cells that had been infected by viruses containing DNA labelled with ^{32}P. The radioactive protein coats had remained outside the bacterial cells, while the radioactive DNA had entered the cells. Hershey and Chase concluded that DNA must be responsible for carrying genetic information. CAREER LINK

The Chemical Composition of DNA

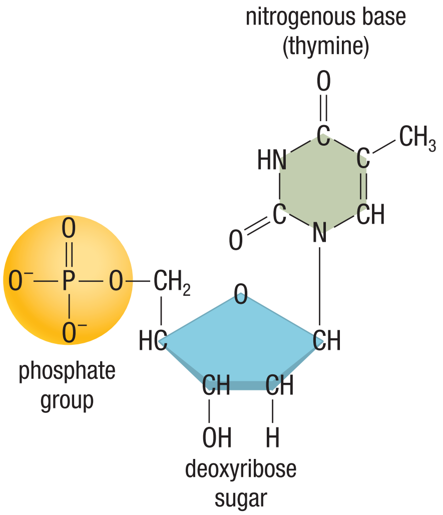
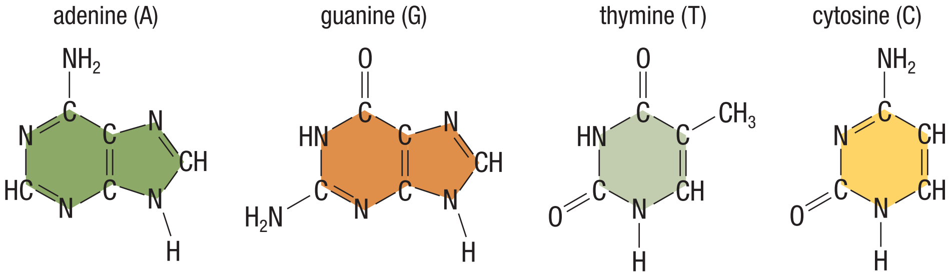


Figure 4 A nucleotide consists of a deoxyribose sugar, a phosphate group, and a nitrogenous base.

Meanwhile, other scientists were researching the molecular composition of Meischer's nuclein. In the 1920s, Phoebus Levene reported that each DNA molecule contained three major components: deoxyribose sugars, phosphate groups, and nitrogenous bases. A DNA molecule is a polymer made of nucleotide subunits. Each nucleotide subunit consists of a nitrogenous base attached to one deoxyribose sugar, which is connected to a phosphate group (**Figure 4**). By 1949, the four nitrogenous bases had been identified (**Figure 5**). Adenine (A) and guanine (G) are double-ring structures known as **purines**, while thymine (T) and cytosine (C) are single-ring structures called **pyrimidines**.

purine a class of nitrogenous bases with a double-ring structure; adenine and guanine are purines

pyrimidine a class of nitrogenous bases with a single-ring structure; thymine and cytosine are pyrimidines



(a) purines **(b)** pyrimidines

Figure 5 The four nitrogenous bases of DNA are classified as either (a) purines or (b) pyrimidines.

Edward Chargaff, an organic chemist, did not agree with researchers who suggested that DNA contained equal amounts of the four nitrogenous bases. In 1950, Chargaff found that these bases always occur in definite ratios. He also found that the quantities of thymine and adenine always matched, as did the quantities of guanine and cytosine. Human DNA, for example, was estimated to contain 30.9 % A, 29.4 % T, 19.9 % G, and 19.8 % C. This information was to prove vital to future research.

Scientists now knew DNA's chemical composition and its role as the molecule of inheritance. However, there were still many unknowns. For example, scientists did not know the structure of the DNA molecule. Nor did they know how the cell made the DNA or how it was passed from parent to offspring.

Wilkins and Franklin: Another Piece of the Puzzle

New discoveries in science are often facilitated by new research technologies. This is certainly true of the research into the chemical composition, structure, and function of DNA. One new technology at that time was X-ray crystallography. This technology involves X-rays bombarding a sample of a compound, which is usually in the form of a solid crystal. The atoms in the compound deflect the X-rays in a specific way, creating a pattern on a photographic plate. The pattern is then analyzed to help determine the molecular structure of the original sample.

Rosalind Franklin and Maurice Wilkins used X-ray crystallography to study the shape of the DNA molecule. They worked somewhat independently on two crystal forms. Although they were colleagues, working in the same laboratory at King's College in London, their relationship was less than congenial. Wilkins had produced some preliminary crystallographs of DNA that suggested its helical structure, but Franklin was unconvinced. Wilkins's DNA samples were poorly prepared, so his crystallographs were difficult to interpret. Franklin prepared much purer crystallized DNA samples and was able to produce some excellent crystallographs. She noticed that the pattern produced by the X-rays was in the shape of an X (**Figure 6**).

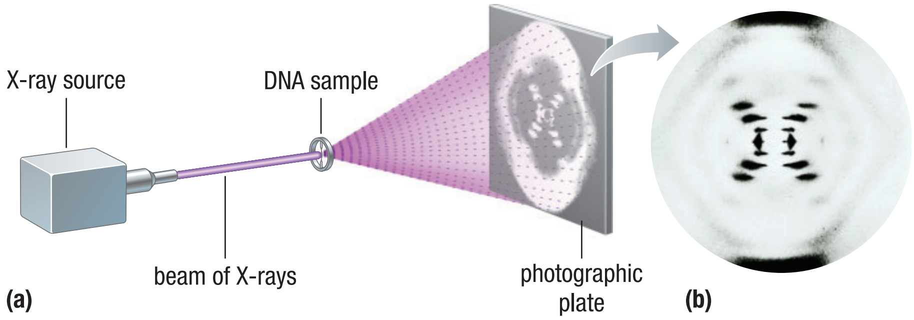


Figure 6 (a) X-ray diffraction was used to study DNA. (b) The X-shaped pattern of spots (dashed lines) that Rosalind Franklin obtained was correctly interpreted by Franklin to indicate that DNA has a helical structure, similar to a spiral staircase.

After analyzing the pattern in her crystallographs, Franklin suggested that the sugar-phosphate backbones of DNA faced the outside of the molecule, not the inside, as was generally believed at the time. She also suggested that DNA was a double helix, which rotated in a clockwise direction. She determined that the DNA molecule had a diameter of 2 nm and that one turn of the helix was 3.4 nm in length. However, she could not explain how the nitrogenous bases were associated in the centre of the helix, even though she was aware of Chargaff's findings. Not wishing to appear incomplete in her analysis, she was hesitant to publish her results.

Watson and Crick: Building a Model of DNA

In science, the synthesis of existing ideas is often just as important as the discovery of new ideas. How a series of discoveries fits together can be the key that unlocks their full meaning. In 1952, the team of James Watson and Francis Crick were building models of the DNA molecule, incorporating everything they knew about DNA. They had a wealth of information available to them:

- four different nitrogenous bases (A, T, C, and G)
- Chargaff's ratios of the nitrogenous bases
- the phosphate and sugar backbone

Without Franklin's knowledge, Maurice Wilkins revealed details of her work to James Watson. The information available to Watson and Crick now included Franklin's ideas about a double helix and inward-facing bases, and her calculations of the size of the DNA molecule. Watson and Crick realized that the double helix could incorporate all of the facts. In their model, each strand of the helix consisted of a phosphate and sugar backbone. The nitrogenous bases were attached to the backbone and directed toward the centre of the molecule. The strands twisted around each other in a clockwise direction. Down the centre of the molecule, each nitrogenous base on one strand was hydrogen bonded with a nitrogenous base on the other strand (**Figure 7**, next page).

Watson and Crick's model showed that the DNA molecule could only be stable if the strands ran antiparallel, that is, if they ran in opposite directions. In other words, one DNA strand must have the hydroxyl of the 3′ carbon attached to the deoxyribose sugar at one end and the phosphate attached to the 5′ carbon of the last sugar at the other end. The other strand must wind around the first with its 5′ end opposite the 3′ end of the first strand (Figure 7). Watson and Crick's model also showed that the nitrogenous bases are connected by hydrogen bonds, keeping the two strands

Investigation **6.2.1**

Extracting DNA from Plants (p. 299)
All life uses DNA for its genetic material, but some cells contain more DNA than others. The number of chromosomes and the number of copies of each chromosome within a cell are directly related to how much DNA the cell contains. In this investigation, you will compare the amount of DNA extracted from different plant species.

Investigation **6.2.2**

Extracting DNA: Design Your Own Experiment (p. 300)
In this investigation, you will examine how changing the experimental protocol affects the yield of DNA from strawberries.

together. The purine and pyrimidine base pairs are linked to each other, according to Chargaff's rules. Therefore, thymine always bonds with adenine by two hydrogen bonds, and guanine always bonds with cytosine by three hydrogen bonds. This is known as **complementary base pairing**. The symmetry is key to the structure of DNA and its ability to divide itself accurately and convey genetic information.

complementary base pairing the chemical tendency of adenine to form hydrogen bonds with thymine, and cytosine to form hydrogen bonds with guanine

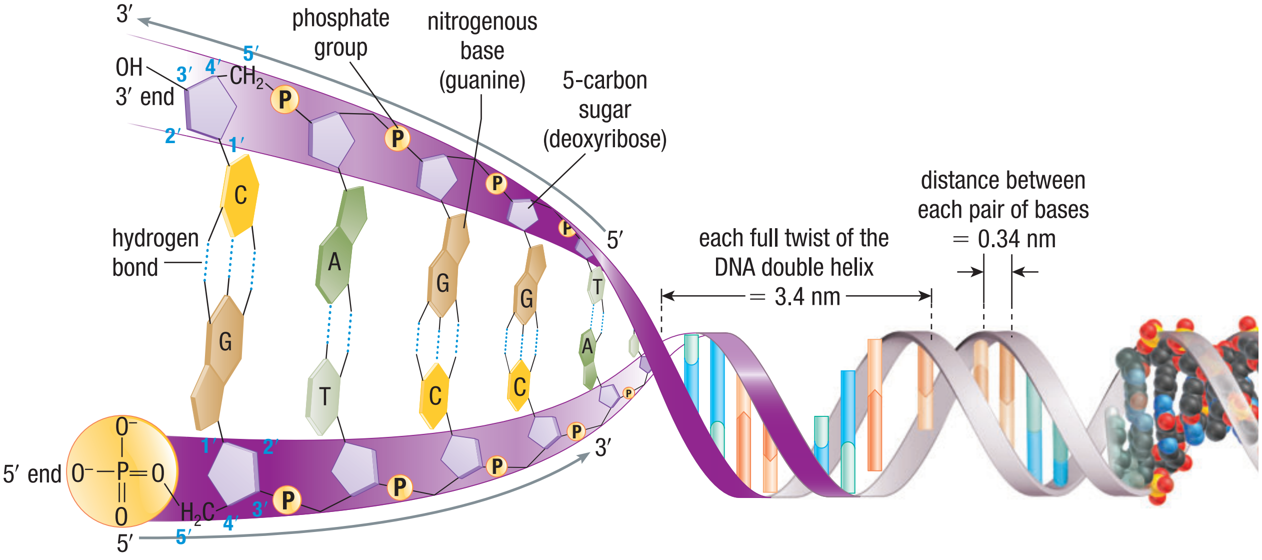

3′
OH
3′ end
3′
4′
5′
CH2
P
2′
1′
phosphate group
nitrogenous base (guanine)
5-carbon sugar (deoxyribose)
hydrogen bond
C
G
A
T
G
C
G
C
T
A
5′
3′
5′ end
O−
O
P
O
O
H2C
1′
2′
3′
4′
5′
5′
each full twist of the DNA double helix = 3.4 nm
distance between each pair of bases = 0.34 nm

Figure 7 DNA is in the shape of a double helix.

Numerous future experiments supported Watson and Crick's model of the DNA molecule. Their work revolutionized our understanding of life and led to many scientific breakthroughs.

Research This

The Collaborative Nature of Science

Skills: Researching, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A4.1

Many scientists contributed to the information that Watson and Crick used to put together their famous model of DNA.

1. Choose one of the following scientists: Frederick Griffith, Oswald Avery, Erwin Chargaff, Alfred Hershey, Martha Chase, Rosalind Franklin, or Maurice Wilkins.
2. Use the Internet and other sources to research the following information about the scientist you chose:
   - the date of the scientist's discovery
   - the experiments that the scientist conducted and where the experiments were conducted
   - the scientist's findings and conclusions
   - the journal in which the scientist's findings and conclusions were published, and when they were published

A. In a one-page report, discuss the contributions of the scientist you researched. In addition to the information in Step 2, include a diagram and answer questions B to E. T/I C

B. How did Watson and Crick use the information discovered by this scientist to help them build their molecular model? T/I

C. Is science collaborative? Use examples from your research and Section 6.2 to support your answer. T/I

D. How does the use of journals enhance the collaboration between scientists? T/I

E. Why is it important that scientists collaborate? T/I C

WEB LINK

6.2 Review

Summary

- Griffith discovered a substance derived from infectious bacteria that could turn non-infectious bacteria into infectious bacteria.
- Avery, McLeod, and McCarty showed that DNA, rather than RNA or protein, was the transforming substance.
- Hershey and Chase confirmed that the DNA of a bacteriophage transformed the DNA of an infected bacterium.
- Chargaff discovered that the nitrogenous bases in DNA always occur in exact ratios, with the number of adenine matching the number of thymine, and the number of cytosine matching the number of guanine.
- Using X-ray crystallography, Franklin and Wilkins provided vital information about the size and shape of the DNA molecule.
- The discovery of the chemical composition, function, and structure of DNA involved the work of numerous scientists over many decades. Watson and Crick combined all of the available information into their double helix model of DNA.
- Each nucleotide in the DNA molecule consists of a deoxyribose sugar, a phosphate group, and one of the four nitrogenous bases. The phosphates and sugars are joined together to form the backbone of each strand. The molecule is double stranded and forms a helix. The two strands of the molecule are antiparallel.

Questions

1. What would Hershey and Chase have concluded if they had found radioactive sulfur instead of phosphorus in infected bacteria cells? K/U T/I
2. The nitrogenous base content of a sample of DNA was found to be 32 % adenine. Determine the amounts of the other three bases in this sample. K/U T/I
3. Describe and sketch the structure of DNA. K/U C
4. Write the complementary strand for the following sequence: GTGACTAACAGTGGCCAT K/U
5. In point-form notes or a timeline, summarize the findings of Frederick Griffith, Oswald Avery, Alfred Hershey and Martha Chase, Erwin Chargaff, Rosalind Franklin, Maurice Wilkins, and James Watson and Francis Crick. K/U C
6. Distinguish between the following substances:
   (a) nitrogenous bases and nucleotides
   (b) purines and pyrimidines
   (c) bacteria and bacteriophages K/U
7. How did the reproductive behaviour of bacteriophages allow Hershey and Chase to conduct their experiment? K/U
8. (a) Why were Avery, McLeod, and McCarty hesitant to report their findings?
   (b) Why is it important for scientists to report their findings? K/U T/I
9. Watson and Crick did not actually conduct any experiments with DNA. Do you think they can be considered scientists? Explain your reasoning. T/I A

The Elucidation of the Structure of DNA

ABSTRACT

Watson and Crick required a great deal of background analysis and insight to develop their model of the double helix structure of DNA. All the information they required came from an ongoing collaboration among scientists. At the same time as the scientists were collaborating, however, they were competing to be the first to publish the exciting discovery of the structure of DNA. Scientific research is always a balance between cooperation and competition. The analysis and insights of Pauling and Corey, Chargaff, and Franklin and Wilkins played an indispensable role in helping Watson and Crick develop their model, which, in itself, was no small accomplishment.

Introduction

The scientific community comprises not only the scientists themselves, but also their collective knowledge and discoveries. One of the defining features of scientific progress is its openness. Scientists from around the world continually share their data, insights, and techniques to push the frontiers of human knowledge.

James Watson and Francis Crick's elucidation of the double helix structure of DNA is a classic example of this process (**Figure 1**). While working on their DNA model, they exchanged ideas and data with many other scientists who were also hoping to be the first to work out the structure of DNA. In this atmosphere of collaboration and competition, Watson and Crick came to their discovery.

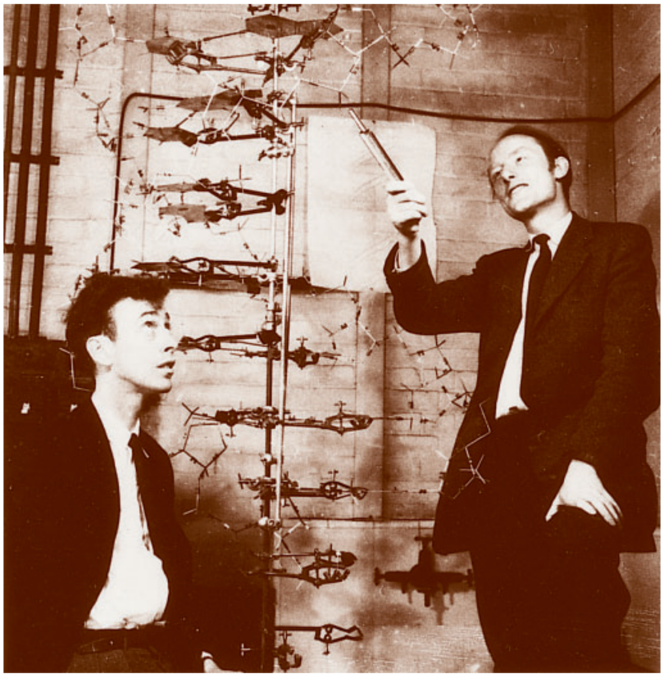


Figure 1 James Watson (left) and Francis Crick

Ideas from Pauling and Corey

Nobel Prize–winning chemist Linus Pauling and biochemist Robert Corey were modelling the structure of DNA at the same time as Watson and Crick. Pauling and Corey's model featured three strands intertwined around each other. Before they sent their article to publication, however, they shared their ideas with Watson and Crick. Pauling was also kind enough to review Watson and Crick's research and offer his own critique and ideas. Watson and Crick mention this collaboration in the opening sentences of their landmark 1953 paper in the prestigious journal *Nature*:

> *We wish to suggest a structure for the salt of deoxyribose nucleic acid (D.N.A.). This structure has novel features, which are of considerable biological interest. A structure for nucleic acid has already been proposed by Pauling and Corey. They kindly made their manuscript available to us in advance of publication. Their model consists of three intertwined chains, with the phosphates near the fibre axis, and the bases on the outside.* WEB LINK

Chargaff's Results

Another unsolved question was how to account for the ratios of the nitrogenous bases. Chargaff published his findings in 1950, showing that the ratios of adenine : thymine and cytosine : guanine were always 1:1. Like all members of the scientific community, Watson and Crick had access to this information through peer-reviewed journals. After they became aware of the inner location of the bases, they incorporated Chargaff's results into their model:

> *The novel feature of the structure is the manner in which the two chains are held together by the purine and pyrimidine bases.... They are joined together in pairs.... One of the pairs must be a purine and the other a pyrimidine for bonding to occur....*

Franklin and Wilkins's Crystallography

In 1952, Rosalind Franklin and Maurice Wilkins produced the first high-resolution crystallographs of DNA. Watson had the opportunity to view the crystallographs because both he and Wilkins were working at Cavendish Laboratory at Cambridge, England. With guidance from Franklin, Watson and Crick realized that Pauling and Corey had the structure inside out. The only solution was to place the phosphates on the outside and have the nitrogenous bases meet in the middle. The problem with Pauling and Corey's model was that the phosphate groups are electrically negative. If they were packed together into the centre of the molecule, they would repel each other, making DNA highly unstable.

Watson and Crick now knew that the sugar-phosphate backbone was on the exterior of the DNA molecule and the bases were joined together in pairs in the interior. The only problem left to solve was the overall shape of the molecule.

There was much debate as to the correct interpretation of the crystallographs produced by Franklin and Wilkins. Franklin initially disagreed with Crick's (ultimately correct) view that the structure of DNA was a double helix. Crick saw in Franklin's crystallographs not only the structure of the molecule, but also the one piece of information that brought everything else together. Understanding their minority opinion, they made clear the uniqueness of their model:

> *We wish to put forward a radically different structure for the salt of deoxyribose nucleic acid. This structure has two helical chains each coiled round the same axis.... Both chains follow right-handed helices ... the two chains run in opposite directions ... the bases are on the inside of the helix and the phosphates on the outside.*

In the end, Franklin agreed with the double helix model. Watson and Crick took care to give collaborative credit where it was due, specifically citing Franklin and Wilkins in the acknowledgments in their article:

> *We have also been stimulated by a knowledge of the general nature of the unpublished experimental results and ideas of Dr. M. H. F. Wilkins, Dr. R. E. Franklin and their co-workers at King's College, London.*

The scientific community understood the importance of this collaboration: Wilkins shared the 1962 Nobel Prize with Watson and Crick. Sadly, Franklin died of cancer in 1958, at the age of 38, and Nobel Prizes are not awarded posthumously. Her cancer may have been caused by exposure to X-rays from her groundbreaking work.

Watson later wrote that Crick had announced their discovery by walking into a nearby pub and blurting out that they had "found the secret of life!" Their keen insight into the importance of their discovery is also found in a sentence near the end of their publication:

> *It has not escaped our notice that the specific pairing we have postulated immediately suggests a possible copying mechanism for the genetic material.*

This note clearly anticipated the research to delineate the process of DNA replication.

Conclusion

Science grows through the interplay of experimentation, interpretation, and rigorous debate. Often, a simple reordering or reinterpreting of existing data offers a key insight. It is not only the pieces of the puzzle that matter, but also how they fit together. Ultimately a human endeavour, science incorporates our collaborative yet competitive natures to attain the goal of knowledge for everyone.

Further Reading

Crick, F.H.C., & Watson, J.D. (1953). A structure for deoxyribose nucleic acid. *Nature*, *171*, 737–738.

Watson, J.D. (1969). *The double helix: A personal account of the discovery of the structure of DNA*. Kolkata, India: Signet Press.

WEB LINK

6.3 Questions

1. Scientific advances are often heavily dependent on technological advances. How is this illustrated in Watson and Crick's 1953 paper? T/I
2. Using Watson and Crick's work as an example, explain how science is both collaborative and competitive. T/I
3. Do you think both competitiveness and collaboration are essential to success in scientific research, or is one more essential than the other? Explain your thinking. T/I

6.4

DNA Replication and Repair

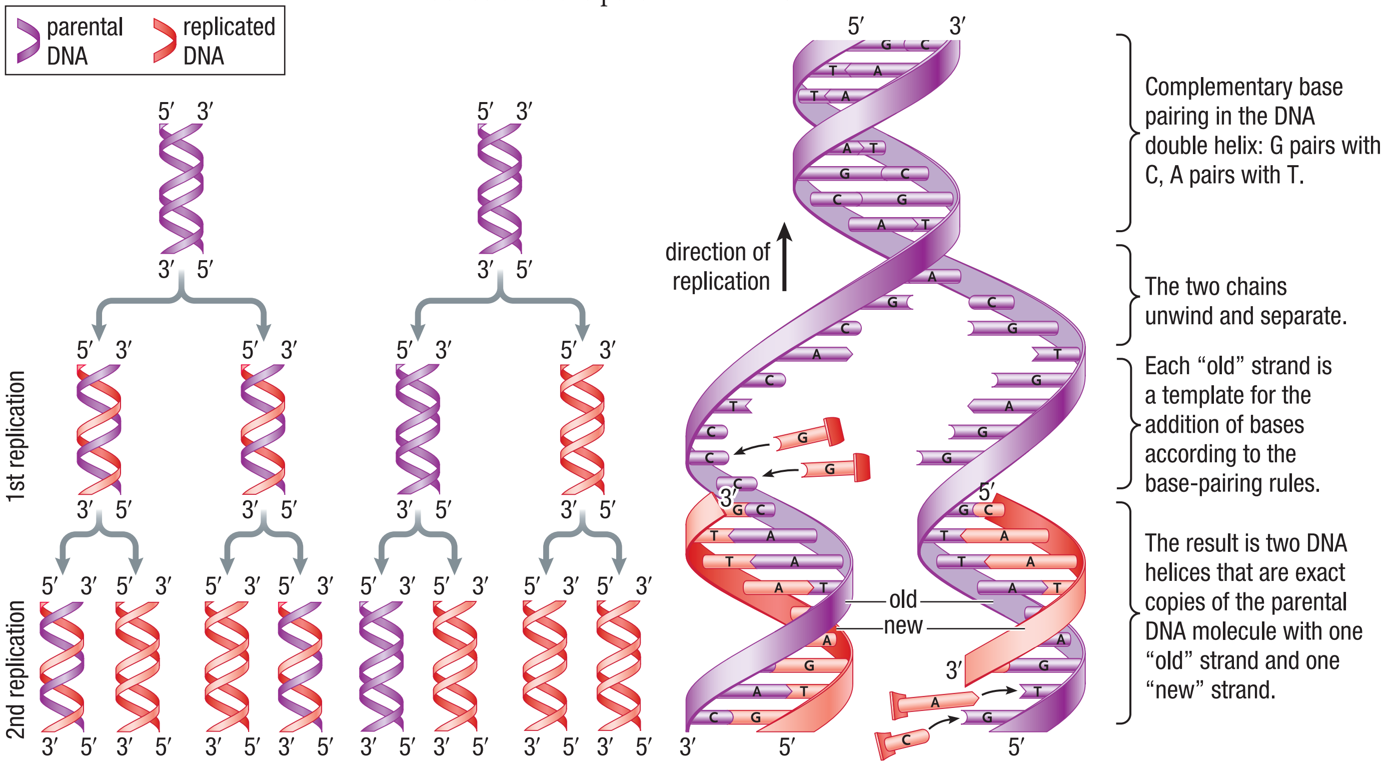
Watson and Crick's double helix model of DNA set the stage for more questions. Scientists knew that DNA replicates itself, but they did not know how. DNA molecules can be millions of nucleotides in length, and replication has to occur very quickly with few (if any) errors. Watson and Crick's new model had to account for this. Scientists now understood the shape, size, and chemical composition of DNA, but they did not know how such a complex and important molecule could replicate itself so well. A great deal of research was needed to understand DNA replication, but Watson and Crick's initial model of the structure of DNA gave scientists a place to start.

DNA Replication Is Semiconservative

Researchers proposed two potential mechanisms of DNA replication: conservative and semiconservative. **Semiconservative replication** would involve separating the two parent strands and building a new, complementary replacement strand for each. The new molecules would consist of one parent strand and one new strand (**Figure 1(a)**). Alternatively, conservative replication would involve copying the DNA molecule "as is," leaving the two original (parent) strands together (**Figure 1(b)**).

semiconservative replication a mechanism of DNA replication in which each of the two strands of parent DNA is incorporated into a new double-stranded DNA molecule

In 1958, Matthew Meselson and Franklin Stahl carried out an experiment that demonstrated that DNA replication is semiconservative (**Figure 1(c)**). Like Hershey and Chase, Meselson and Stahl used isotopes to label the parent DNA strands before replication. The isotope they used was "heavy" nitrogen, ^{15}N. *E. coli* bacteria were grown for 17 generations in a medium that contained ^{15}N, until all the cells had incorporated it completely into their DNA. Meselson and Stahl then transferred the bacteria to a medium that contained only normal, "light" nitrogen, ^{14}N, and allowed one or two rounds of replication (approximately 20 min each). Any new DNA produced should have lighter ^{14}N incorporated into its structure, thus making it less dense than the parent ^{15}N DNA.



Complementary base pairing in the DNA double helix: G pairs with C, A pairs with T.

The two chains unwind and separate.

Each "old" strand is a template for the addition of bases according to the base-pairing rules.

The result is two DNA helices that are exact copies of the parental DNA molecule with one "old" strand and one "new" strand.

(a) semiconservative replication **(b)** conservative replication **(c)** DNA replicates semiconservatively

Figure 1 (a) In semiconservative replication, the two parental strands would act as templates for replication and remain separated from each other, incorporated into two new molecules. (b) In conservative replication, the two parental strands would act as templates for replication, but then recombine afterwards. (c) DNA undergoes semiconservative replication.

To determine the density of the DNA, the DNA was isolated and placed in a centrifuge tube that contained a mixture that, when centrifuged, produces a density gradient from most dense at the bottom to least dense at the top. DNA migrates to a level in the tube with a density similar to its own. In this way, heavy parental ^{15}N DNA could be isolated from any new, less dense ^{14}N DNA.

After centrifuging, the original heavy ^{15}N DNA was in a single band (**Figure 2(a)**). After one round of replication, there was a single band of DNA at a density that was consistent with hybrid DNA—DNA containing equal parts of ^{15}N and ^{14}N (**Figure 2(b)**). If replication had been conservative, two bands would have been seen, one containing the parental ^{15}N DNA and one containing only new ^{14}N DNA. The single band of hybrid DNA, lying between these two positions in the gradient, confirmed that DNA replication was indeed semiconservative. Each single strand of parental DNA had been used as a template for a new complementary ^{14}N DNA strand to be built.

The results of centrifuging after two rounds of replication confirmed this conclusion. Two bands of DNA were detected: one that had a density consistent with hybrid DNA and one that corresponded to DNA built only with light ^{14}N nucleotides (**Figure 2(c)**). Each double strand of hybrid DNA had been separated and used to build complementary ^{14}N strands, producing one band of hybrid DNA and one with only ^{14}N. The clarity of the results of Meselson and Stahl's elegant and innovative experiment left little doubt. DNA replication is semiconservative.

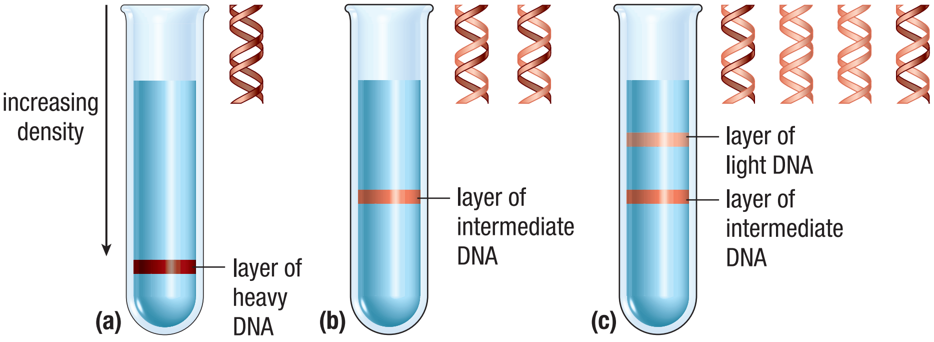


Figure 2 Results of Meselson and Stahl's experiment: (a) position of the original parent heavy ^{15}N DNA, (b) position of hybrid DNA produced after one round of DNA replication, and (c) positions of DNA formed after two rounds of replication

DNA Replication: The Process

Most of our understanding of the process of DNA replication comes from the study of the bacterium *E. coli*. Replication in eukaryotes is similar to replication in prokaryotes in most ways. However, the linear configuration of eukaryotic DNA and its sheer volume in a cell means that the process is more complex. DNA replication has three steps. First, the parental strands of DNA separate. Second, the complementary DNA strands are assembled. Third, the new strands are proofread and repaired.

Step 1: Strand Separation

To begin replication, the DNA strands must be unwound from each other (**Figure 3**, next page). Specific nucleotide sequences on the genome, called **replication origins**, act as starting points. Due to the length of DNA molecules in eukaryotes, there are many replication origins on a DNA strand. An enzyme called **helicase** binds to these origins and begins to unwind the two strands of DNA by breaking the hydrogen bonds between the complementary base pairs. As the two strands separate, they form a Y-shaped structure known as the **replication fork**.

This seemingly simple separation presents two challenges. First, if you have ever tried to separate the fibres in a rope or string by pulling them apart, you know that the tension

replication origin a specific sequence of DNA that acts as a starting point for replication

helicase a replication enzyme that separates and unwinds the DNA strands

replication fork the point of separation of the two parent DNA strands during replication

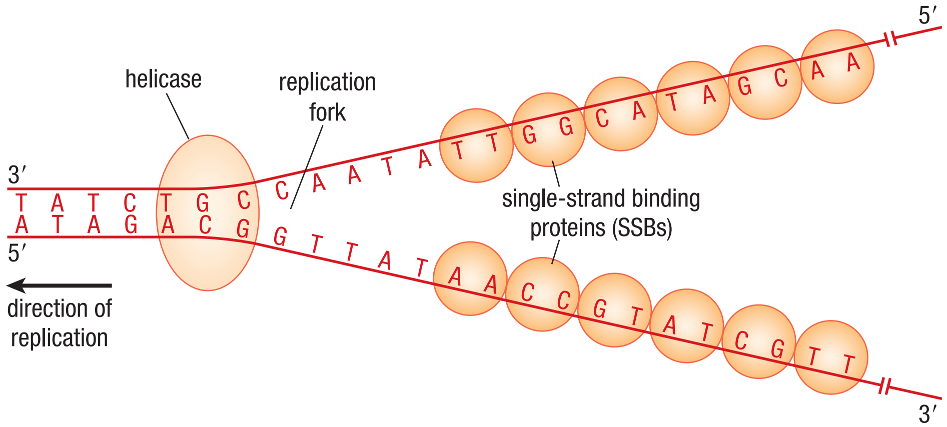

5′
helicase
replication fork
3′
T A T C T G C C A A T A T T G G C A T A G C A A
A T A G A C G G T T A T A A C C G T A T C G T T
5′
single-strand binding proteins (SSBs)
direction of replication
3′

Figure 3 The double-stranded DNA is unwound by helicase. Single-strand proteins bind to the exposed bases to prevent them from annealing (reattaching).

created can lead to twisting and tangles. A class of enzymes called **topoisomerases** relieves this tension in DNA strands by cutting one or two of the strands near the replication fork, allowing the strands to untangle, and then rejoining the cut strand(s). Second, after the two strands are separated, they have a tendency to rejoin, or anneal, because they are complementary. **Single-strand binding proteins (SSBs)** prevent annealing by attaching to the DNA strands to stabilize them and keep them separated (Figure 3). These proteins are removed during the next phase of replication but are used again when needed.

topoisomerases a class of enzymes that relieve tension caused by the unwinding of parent DNA; they cleave one or two of the DNA strands, allow the strand(s) to untwist, and then rejoin the strand(s)

single-strand binding protein (SSB) a replication enzyme that prevents parent DNA strands from annealing to each other once they have been separated by helicase

Helicase complexes can separate DNA strands in both directions from a replication origin. Soon after separation, new complementary nucleotides are added to the naked strands. As the two replication forks proceed in opposite directions, the space between them that is filled with newly replicated DNA is called a **replication bubble** (**Figure 4**). Due to the great length of eukaryotic DNA, there are many replication bubbles along a DNA strand. Each bubble expands along the length of the molecule until it meets and merges with another bubble, eventually producing two separate daughter strands.

replication bubble the separating of DNA in both directions during replication

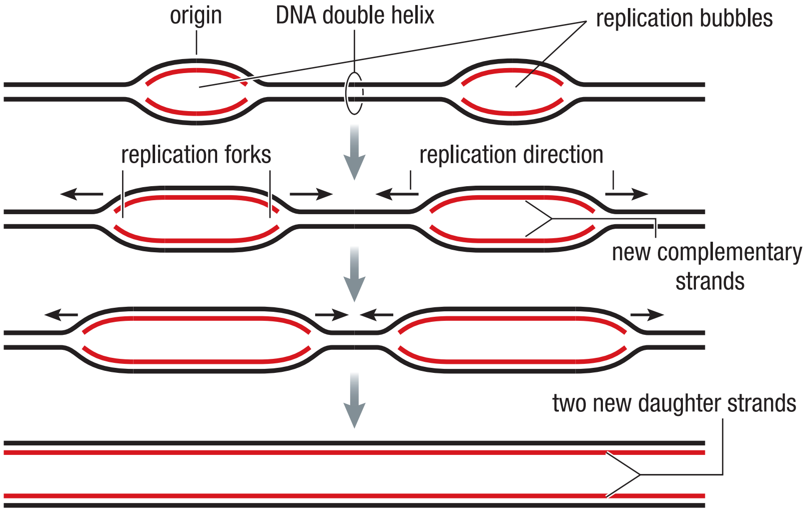


Figure 4 Replication bubbles form, grow, and merge.

If it were not for multiple replication origins, each producing a replication bubble, replicating the genome of a typical human would take an impractical amount of time. In eukaryotes, new DNA is made at the rate of about 50 base pairs per second at each replication fork. At this rate, if the replication process depended on only one replication origin, the entire genome of a human would be reproduced in about a month. Multiple replication origins decrease the time to about 1 h.

Step 2: Building Complementary Strands

During replication, new nucleotides are joined by a group of enzymes called DNA polymerases. Although both prokaryotes and eukaryotes have DNA polymerases, the following description will refer to the polymerases that occur in prokaryotes. Eukaryotes have several more specialized DNA polymerases, and the system is quite complex.

Prokaryotic DNA polymerases add nucleotides to the 3′ end of a new developing strand while moving along and "reading" the template strand in its 3′ to 5′ direction (**Figure 5(a)**). This is the important feature of DNA polymerases: they can only add nucleotides to the 3′ end of an existing DNA (or RNA) strand. Therefore, the new strand is always assembled in the 5′ to 3′ direction. You will learn more about this later.

DNA polymerase builds the new strand of DNA using **nucleoside triphosphates** (**Figure 5(b)**). These molecules are very similar to the nucleotides in the finished DNA. They contain a deoxyribose sugar bonded to one of the four nitrogenous bases (adenine, thymine, cytosine, or guanine), as well as a group of three phosphate molecules. Figure 5 shows how the nucleoside triphosphates are joined to the growing DNA strand.

nucleoside triphosphate a building block and energy source for replicating DNA

For a new strand to be built, energy is needed to power the reactions carried out by the DNA polymerase (**Figure 5(c)**). This energy is provided by the phosphate groups attached to the nucleoside molecule. Energy is released by the hydrolysis reaction that cleaves two phosphates from the nucleoside triphosphate and by the formation of the phosphodiester bond between the one remaining phosphate and the hydroxyl group on the 3′ carbon at the 3′ end of the growing DNA strand. The two released phosphates are hydrolysed to two inorganic phosphates (P_i). The energy released is also used to drive DNA synthesis.

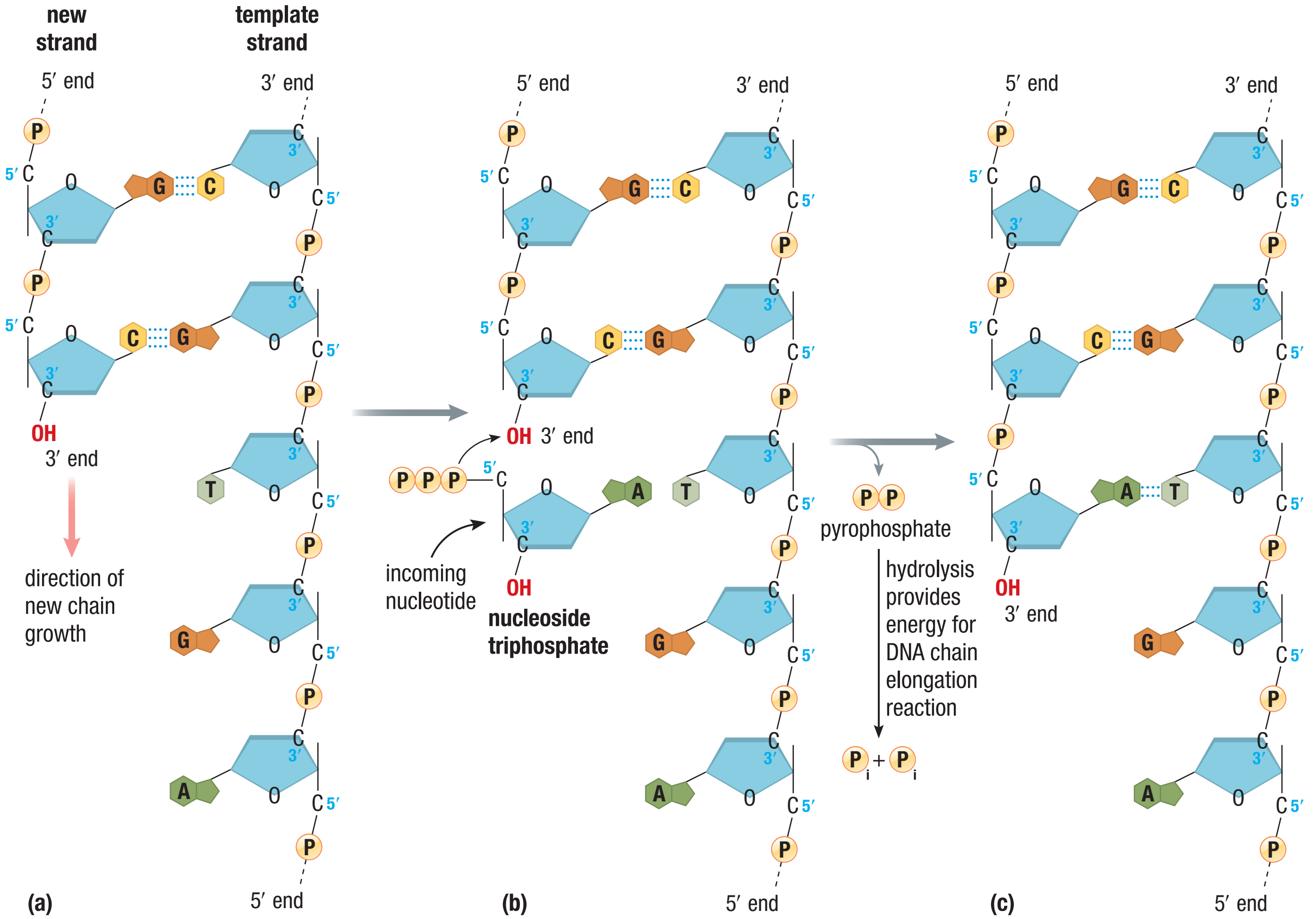


Figure 5 New nucleotides are added to the 3′ end of the new strand. (a) The template strand is read as two nucleotides are assembled on the new strand. (b) A nucleoside triphosphate with an A base forms a complementary base pair with the next nucleotide of the template strand. (c) A phosphodiester bond forms, linking the newly added nucleotide to the end of the new strand.

RNA primase a replication enzyme that produces RNA primers

RNA primer a replication molecule that acts as a starting point for replication

DNA polymerase III a prokaryotic replication enzyme that builds new DNA strands from nucleotides

When a replication fork first opens, there is nothing for DNA polymerase to "add to." Recall that DNA polymerase can only assemble a strand by adding nucleotides to the 3′ end of an existing strand. To overcome this problem, **RNA primase** enzymes begin the replication process by building a small complementary RNA segment on the strand at the beginning of the replication fork (**Figure 6(a)**, next page). These short, 10 to 60 ribonucleotide pieces of RNA are called **RNA primers**. As the replication fork continues to open and separate the parent strands, one strand is oriented in the 3′ to 5′ direction while the other is oriented in the opposite 5′ to 3′ direction. Once an RNA primer is in place, the enzyme **DNA polymerase III** begins adding DNA nucleotides to the RNA primer. Since DNA polymerase III only builds the new strand in the 5′ to 3′ direction, the two new strands begin to be assembled in opposite directions (**Figure 6(b)**, next page). The result is that, as the replication fork continues to open, the DNA polymerase III that is building a strand toward the fork is able to keep moving forward continuously. There is no need, nor opportunity, for RNA primase to add any additional primers to the strand. This strand is called the **leading strand**.

leading strand the DNA strand that is copied in the direction toward the replication fork

lagging strand the DNA strand that is copied in the direction away from the replication fork

Okazaki fragment the piece of new DNA on the lagging strand

On the opposite strand, however, DNA polymerase III is moving away from the opening replication fork. This strand is the **lagging strand**. When enough fork has opened, RNA primase attaches another primer to the parent strand, allowing another DNA polymerase III to begin from the new starting point. The pattern created on the second strand is a series of RNA primers and short DNA fragments called **Okazaki fragments**. Okazaki fragments are thought to be between 1000 and 2000 bases long in prokaryotes and much shorter (between 100 and 200 nucleotides long) in eukaryotes. Because the second strand is not made in one continual process, it is called the lagging strand (**Figure 6(c)**, next page).

DNA polymerase I a prokaryotic replication enzyme that fills in gaps in the lagging strand between Okazaki fragments; also proofreads the final strands

DNA ligase an enzyme that catalyzes the formation of a phosphodiester bond between two DNA strands, as well as between Okazaki fragments

As each fragment extends in the 5′ to 3′ direction, it eventually runs into the RNA primer attached to the Okazaki fragment ahead of it. Another polymerase, **DNA polymerase I**, removes the RNA nucleotides one at a time and replaces them with DNA nucleotides. Once the primer is replaced, the last nucleotide is linked to the Okazaki fragment in front of it by the formation of a phosphodiester bond. An enzyme called **DNA ligase** catalyzes this reaction (**Figure 6(d)**, next page). Eventually, all the RNA primers are removed and replaced by DNA (**Figure 6(e)**, next page).

Step 3: Dealing with Errors during DNA Replication

The DNA polymerase enzymes that carry out replication play another important role. As they assemble the new DNA strands, they proofread and correct errors. These errors are usually base-pair mismatches. For example, if a thymine is added across from a cytosine, they cannot form hydrogen bonds and the strand is unstable. DNA polymerase III cannot move forward if base pairs are mismatched (**Figure 7(a)**, page 288). It usually backs up, replaces the incorrect base with the correct one, and then continues on.

DNA polymerase II a prokaryotic replication enzyme that repairs damage to DNA, including damage that occurs between replication events

After a strand has been replicated, rare mismatching errors may still be present—usually an average of only one error for every million base pairs. However, even this low number of errors could have serious implications for an organism. Special DNA repair complexes read the strands for errors that might have been missed by DNA polymerase III. These repair complexes are composed of proteins and enzymes, including DNA polymerase I and **DNA polymerase II**. DNA polymerase II is a slow enzyme and often works to repair damage to DNA that occurs between replication events. Since mismatched base pairs cannot bond correctly, they distort the shape of the DNA. The DNA repair complexes move along the strand, locating these distortions. Once a distortion is found, a repair complex determines which of the two helices contains the incorrect base. The repair complex can even recognize the original (correct) strand! An enzyme removes a portion of the strand around the mismatch. The resultant gap is filled in by a DNA polymerase and completed with DNA ligase (**Figure 7(b)**, page 288).

Similar repair mechanisms help to correct damage caused by chemicals and radiation, including ultraviolet light. Without these repair mechanisms, DNA would accumulate many errors. The errors could lead to the loss or change of function, or even cancer.

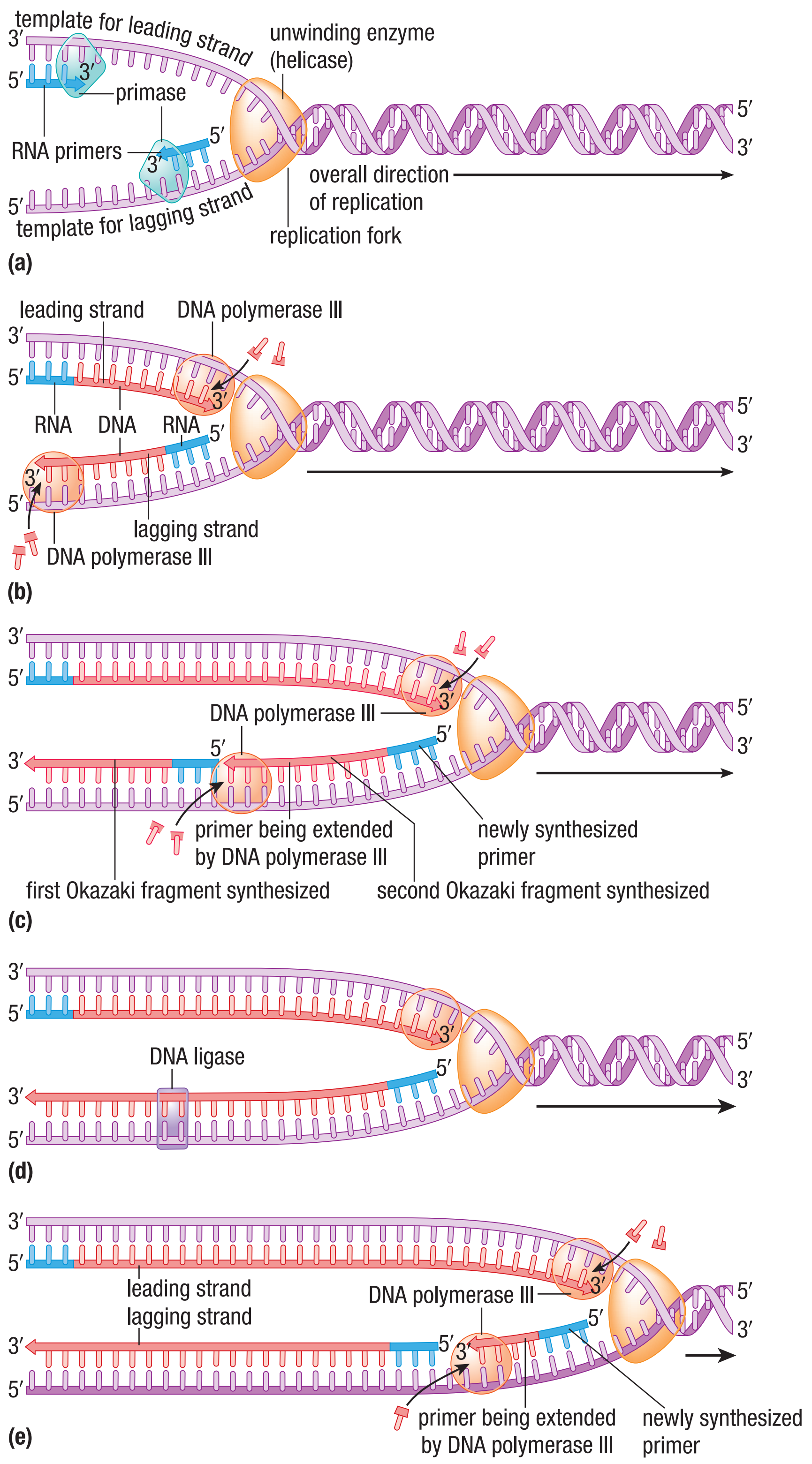
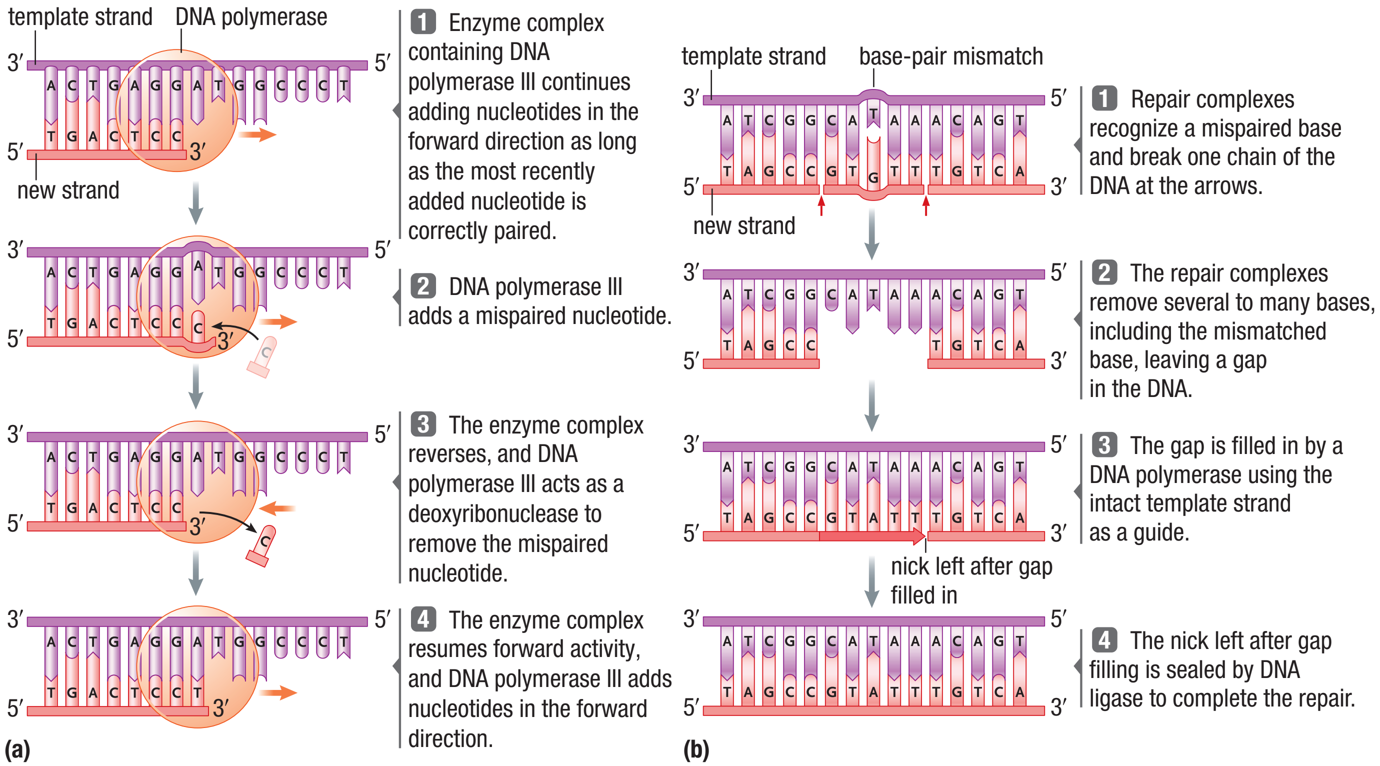


Figure 6 (a) As the replication fork opens, RNA primase attaches RNA primers to both the leading and lagging strands. These primers are oriented in opposite directions. (b) A DNA polymerase III enzyme attaches to the 3′ end of each primer and begins assembling the new DNA strands in opposite (5′ to 3′) directions. (c) As the replication fork continues to open, the new leading strand continues to be assembled in one continuous process. On the lagging strand, a new RNA primer is attached and DNA polymerase III begins assembling a new DNA fragment. (d) The resulting DNA fragments are then joined by DNA ligase. (e) The entire process results in the formation of two new daughter DNA molecules: one consisting of a parent strand and the new leading strand, and the other formed by the other parent strand and the new lagging strand.



1 Enzyme complex containing DNA polymerase III continues adding nucleotides in the forward direction as long as the most recently added nucleotide is correctly paired.

2 DNA polymerase III adds a mispaired nucleotide.

3 The enzyme complex reverses, and DNA polymerase III acts as a deoxyribonuclease to remove the mispaired nucleotide.

4 The enzyme complex resumes forward activity, and DNA polymerase III adds nucleotides in the forward direction.

1 Repair complexes recognize a mispaired base and break one chain of the DNA at the arrows.

2 The repair complexes remove several to many bases, including the mismatched base, leaving a gap in the DNA.

3 The gap is filled in by a DNA polymerase using the intact template strand as a guide.

4 The nick left after gap filling is sealed by DNA ligase to complete the repair.

Figure 7 Repair mechanisms fix damage and base-pair mismatches. (a) DNA polymerase enzymes proofread the new DNA strands. (b) Mismatched bases in replicated DNA are repaired.

As you have seen, the process of DNA replication requires many enzymes and other molecules. **Table 1** summarizes their functions. WEB LINK

Table 1 Enzymes and Other Molecules Involved in DNA Replication

Enzyme/Molecule	Function
helicase	unwinds DNA helix
single-strand binding protein (SSB)	stops the two separated parent strands from annealing
topoisomerases	cleave and then reattach one or two of the DNA strands to relieve tension created by the unwinding process
RNA primase	places RNA primers on template strands
RNA primers	act as starting strands for DNA polymerase
DNA polymerases	several closely related enzymes that assemble nucleotides into new DNA strands; remove RNA primer nucleotides and replace them with DNA nucleotides; proofread and repair replication errors and other damage to DNA molecules
DNA ligase	forms the phosphodiester bond that joins the ends of DNA that make up the Okazaki fragments

DNA Replication in Prokaryotes and Eukaryotes

As mentioned at the beginning of this section, most of our knowledge of DNA replication has come from the study of bacteria. Research into DNA replication in eukaryotes has confirmed that the process is essentially the same. However, due to differences in genomic content and structure, there are some differences in the process in eukaryotes. For example, the genomes of prokaryotes are much smaller than the genomes of eukaryotes and are circular in structure. Usually only one replication origin and only one replication bubble occur. Eukaryotic genomes are very long and linear, necessitating thousands of origins and as many replication bubbles. The ends of linear DNA strands also present a replication dilemma, which you will learn about in Sections 6.5 and 6.6.

Another difference occurs in the enzymes that are involved in DNA replication and repair. The polymerases identified in this section are found in bacteria. The DNA polymerases that are found in eukaryotes are more varied, but they function in the same way.

As new research reveals the intricacies of DNA replication in prokaryotes and eukaryotes, new possibilities become increasingly apparent. Understanding DNA replication could have significant implications in the control of growth, aging, cloning, tissue regeneration, cancer, and biotechnology in general. Scientists did not even know what DNA looked like 60 years ago. Now, every question that is answered brings new questions to the forefront.

Investigation 6.4.1

Role-Playing DNA Replication (p. 301)
In this activity, you will demonstrate your knowledge and understanding of DNA replication by designing a role-play with some of your classmates.

Mini Investigation

Constructing a Model of DNA Replication

Skills: Performing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

The structure of DNA ensures that replication occurs with a minimal number of errors. In this investigation, you will model DNA replication, and then compare your model to what you know about the process. For simplicity, you will ignore the need for RNA primers during the process.

Equipment and Materials: ruler; scissors; coloured paper (white, red, blue, brown, green, and black); transparent tape

1. Work in a group. Divide the task of cutting out pieces of paper among the group members (**Table 2**). Write the capital letter for the name of each part of the DNA model on the correct piece of paper.

Table 2 Coloured Pieces of Paper

Part of DNA model	Colour	Size (cm x cm)	Number needed
sugar	white	2 x 2	72
phosphate	red	1 x 2	72
adenine	blue	1 x 2	16
thymine	brown	1 x 1	16
guanine	green	1 x 2	20
cytosine	black	1 x 1	20

2. Construct a nucleotide of thymine by taping together a sugar, a phosphate group, and a thymine, using the correct configuration as shown in Figure 4, page 276 (Section 6.2).
3. Assemble other nucleotides using the other three bases.
4. Assemble one strand of DNA with a sequence of 5′-TCCGTAGAACTGTGATTA-3′. Label the 5′ and 3′ ends.
5. Assemble the complementary strand of DNA. Be sure that it is antiparallel to the first side. Label the 5′ and 3′ ends.
6. Label the back of each strand as "original parent strand." Do not tape the strands together.
7. Lay the two strands so that the base pairs line up according to base pairing rules. Gently slide them apart at one end. The other end should still be touching. This action models the formation of the replication fork.
8. DNA polymerase reads an original strand from 3′ to 5′ and adds complementary nucleotides in the 5′ to 3′ direction. Simulate this by adding complementary nucleotides one at a time. Follow the base-pairing rules to make sure that you add the correct nucleotide. You should be adding nucleotides and building the new strand toward the replication fork. This represents the leading strand.
9. At any point on the other original strand, begin adding nucleotides. Be sure to add them in the correct direction (5′ to 3′), away from your replication fork. The section you have built represents an Okazaki fragment. As you continue to open the replication fork, make another Okazaki fragment toward the first. When this fragment meets the end of the first fragment, join the two fragments. The strand you are building represents the lagging strand.
10. Once the original strands have been totally separated, and complementary nucleotides have been added to each strand, you should have two "ladders." Each ladder should have one old strand and one new strand.
11. To model a DNA molecule, tape each template strand to its newly synthesized complementary strand.

A. What type of bonding does the tape in Step 11 represent? T/I

B. Why is DNA said to replicate semiconservatively? Explain by referring to your model. K/U C

C. Your two new strands were not replicated in the same direction. Why? K/U T/I

D. Go online and watch a few DNA replication simulations and animations. From your knowledge of DNA replication, comment on the accuracy of each simulation or animation. Which would you recommend to your classmates? T/I

WEB LINK

6.4 Review

Summary

- DNA is copied by semiconservative replication. Each strand of the original DNA is incorporated into one of the new copies.
- When DNA strands separate, topoisomerases help relieve tension caused by unwinding, and single-strand binding proteins (SSBs) prevent strands from rejoining.
- Replication occurs in the general direction toward the replication fork, and always in a 5′ to 3′ direction on the newly synthesized strand. This results in a leading (continuously replicated) strand and a lagging strand. The lagging strand consists of Okazaki fragments.
- All replication begins with the formation of RNA primers on the parent DNA strands. DNA polymerases begin the synthesis of new DNA strands on the 3′ ends of the RNA primers. The primers are later replaced with DNA by DNA polymerase I.
- Base-pair mismatching can occur during replication. DNA polymerase and other repair enzymes proofread the strands for errors and correct mismatched bases.
- DNA replication in prokaryotes and eukaryotes differs.

Questions

1. (a) Without looking at the text, try to list and summarize the three steps that are involved in replication.
   (b) Check what you wrote. What did you miss? Did you miss anything that is crucial to the replication process? K/U
2. Place the following enzymes in the order in which they are used in DNA replication: topoisomerase, DNA ligase, DNA polymerase III, RNA primase, helicase, DNA polymerase I. K/U
3. What would happen if each of the following were not available for DNA replication? How would this affect the process? K/U T/I
   (a) topoisomerase
   (b) DNA ligase
   (c) single-strand binding protein
4. Explain why the process of DNA replication is slower on the lagging strand than on the leading strand. K/U T/I
5. Is DNA an example of a polymer? Explain. K/U
6. Why can both template strands not be replicated continuously? K/U
7. Helicase separates and unwinds the DNA strands from each other. Why is an enzyme not required to bring the strands back together (re-anneal them)? T/I
8. Upon examining an organism, you discover that it produces DNA polymerase III but does not produce DNA polymerase I. Describe two possible scenarios that could be occurring in this organism during DNA replication. Include the assumptions that you must make. K/U T/I
9. During your examination of an alien life form, you notice the DNA replication proceeds in both directions. What questions about the DNA replication would you investigate? Why? K/U T/I A
10. When Watson and Crick first proposed their double helix model of the DNA molecule, they suggested a semiconservative mode of DNA replication. Explain why their model justifies the semiconservative mode of reproduction. K/U T/I
11. Without DNA repair, an organism is likely to suffer from significant problems. Xeroderma pigmentosum is a serious human disorder that is caused by mutations in the gene for DNA repair. Do online research to determine the symptoms that are associated with this disorder. What type of DNA damage are individuals with this disorder most susceptible to? T/I

WEB LINK

DNA Organization in Eukaryotes and Prokaryotes

If you unravelled all the chromosomes in a single human cell, isolated the DNA, and then joined all the double helices end to end, the molecule you produced would be about 1.8 m long. This entire length of DNA must fit into a cell nucleus that is only 10 µm across. What strategies has life evolved to make it fit?

The Packing of Eukaryotic DNA

Imagine that you are trying to store a garden hose. The hose takes up much less space if you coil it neatly around a spool. This is exactly what happens in eukaryotic cells. DNA is wound around special proteins, called histones, that act like spools (**Figure 1**).

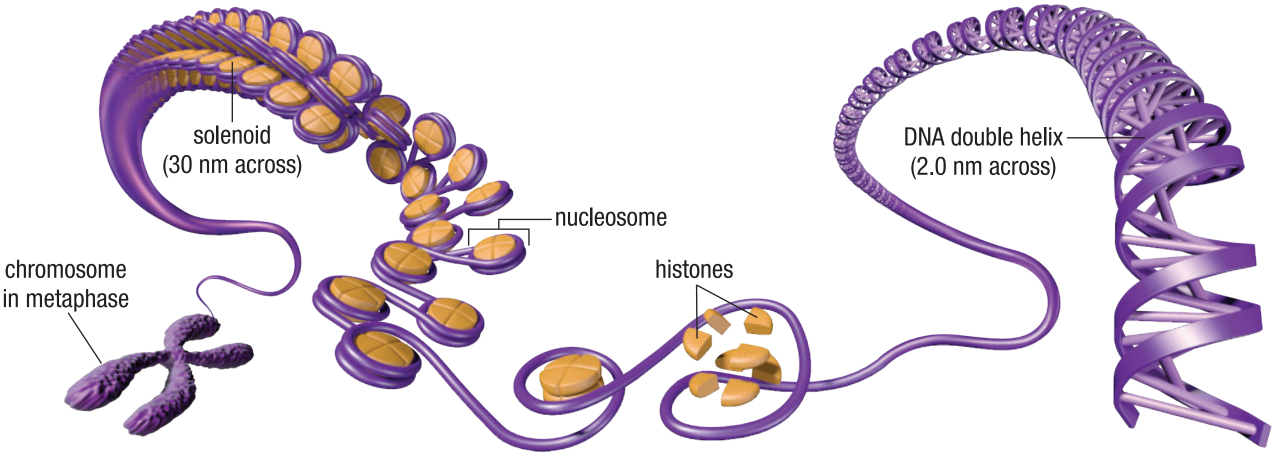


Figure 1 To fit inside the nucleus, DNA strands wrap around clusters of eight histone proteins to form a nucleosome. Further packing reduces the volume of six nucleosomes to just 30 nm. A length of about 147 nucleotides is wrapped around each group of histones.

Histones are positively charged proteins, and the negatively charged DNA strands are attracted to them. This attraction causes the DNA strands to wrap tightly around a cluster of eight histones, greatly reducing the amount of space that the DNA occupies. Each unit, consisting of eight histone proteins and the wrapped DNA, is called a **nucleosome** (Figure 1). Stretches of DNA, called linkers, connect one nucleosome to the next. At this level of organization, the strands of chromatin appear like a string of beads.

nucleosome a unit of DNA storage, consisting of eight histones with DNA strands wrapped around them; the DNA around each nucleosome is about 147 nucleotides in length

The volume of the DNA has now been reduced by a factor of seven. Further packing of the DNA is accomplished by coiling strings of nucleosomes into cylindrical fibres with a diameter of 30 nm (3.0×10^{-10} m). These are commonly known as 30 nm chromatin fibres, but they are also called **solenoids**. Each coil of a solenoid contains six nucleosomes (Figure 1).

solenoid a group of six nucleosomes

Most of the DNA in the nucleus during the interphase stage is in the form of loosely packed nucleosomes or solenoids. If the DNA contains active genes, the nucleosomes must be altered to allow the proteins and enzymes that are needed for gene expression to access the coding sequences of the bases. Histone molecules may even assist in the regulation of this process. If the DNA contains inactive genes or non-coding sections of genes, the solenoids function as compact storage units that protect the DNA from potential damage. When a cell enters the reproductive stage of its life cycle, the solenoids can be further supercoiled to form the typical X-shaped chromosomes that are visible during the metaphase stage of mitosis.

Mini **Investigation**

Packing DNA

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A2.1

Cells have evolved mechanisms for storing large amounts of DNA in small spaces. In this investigation, you will attempt to mimic the storage process using a piece of thread (representing the DNA) and a pill capsule (representing a human cell nucleus).

Equipment and Materials: empty gelatin capsule (gel cap); 2 m piece of thread

1. Using any strategy, try to fit the 2 m piece of thread into the gel capsule.

A. Were you successful in fitting all the thread into the capsule? Why or why not? T/I

B. How does this activity mimic the packing of DNA into a cell nucleus? T/I

C. How does this activity differ from the packing of DNA into a nucleus? T/I

D. What advantage might there be in having DNA packed as chromatin rather than free-floating? T/I

E. The gel capsule is approximately 1000 times the size of an actual human cell nucleus. The thread is the same length as the real DNA in a single human cell. Real DNA, however, is only about 2.5 nm wide, while the thread you used is perhaps 500 000 nm across. How would your results have changed if the thread had been the true thickness? T/I

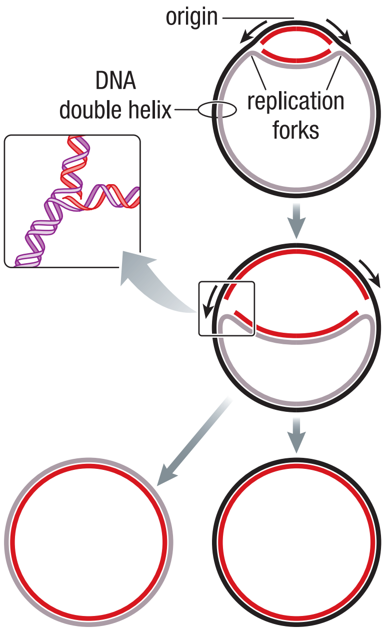


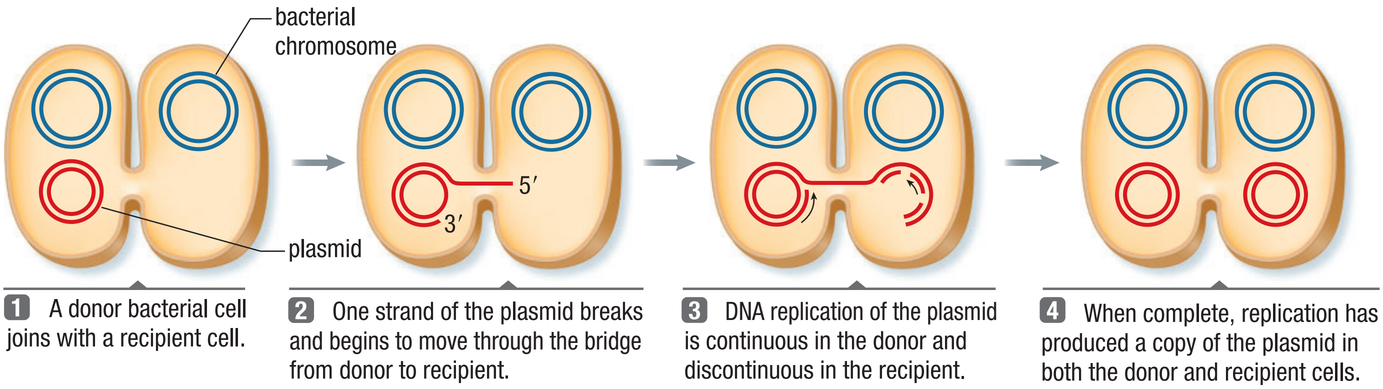
Figure 2 Prokaryotic DNA is one long chromosome that may be circular.

Prokaryotic DNA Organization

The organization of DNA in both eubacteria and archaea is simpler and has other features that set it apart from eukaryotic DNA. In this section, however, the discussion will be limited to DNA organization in eubacteria. The bacterial DNA consists almost entirely of one chromosome that is commonly circular (**Figure 2**). Linear chromosomes do occur in some forms of bacteria, but they are rare. Unbound by a nuclear membrane, the DNA is less tightly bound and more easily accessed by the enzymes and other molecules involved in replication than eukaryotic DNA is.

In addition to the primary circular DNA, smaller circular pieces of DNA float throughout the cell. In a process called conjugation, these smaller circular pieces of DNA, called plasmids, are able to exit one cell and enter another. When two bacteria are close together, a plasmid in one bacterium can pass into the other. The recipient bacterium incorporates the new plasmid into its genome (**Figure 3**). This feature allows natural variation of bacteria and is very useful for genetic engineering research, since it allows scientists to insert plasmids with desired genes into host bacteria. (You will learn about genetic engineering in Chapter 8).

Despite the simplicity of their genomes, prokaryotes face the same problem as eukaryotes when packing their DNA into a small cell. Whereas eukaryotes have additional proteins that package their DNA, prokaryotes use a coiling technique. Imagine (or try) twisting an elastic band so that it forms tiny coils along its length. Then keep



1 A donor bacterial cell joins with a recipient cell.

2 One strand of the plasmid breaks and begins to move through the bridge from donor to recipient.

3 DNA replication of the plasmid is continuous in the donor and discontinuous in the recipient.

4 When complete, replication has produced a copy of the plasmid in both the donor and recipient cells.

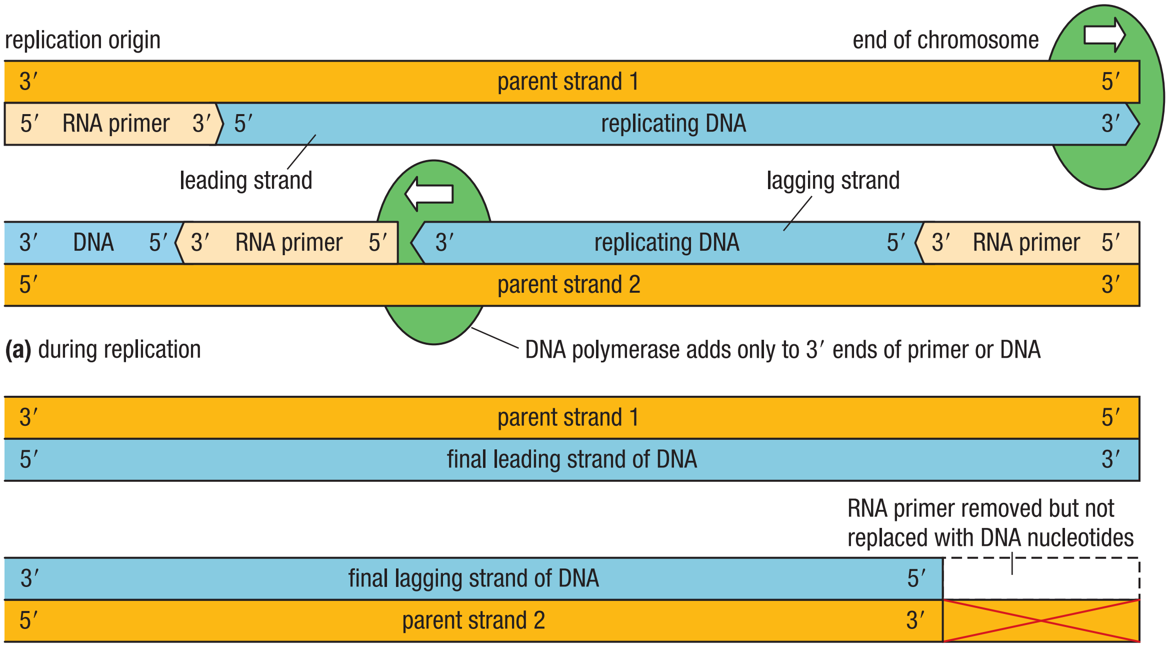
Figure 3 Neighbouring bacteria can replicate plasmids, donating the replicated plasmid to the other bacterium.

twisting the elastic band until the coils bunch on top of each other and form a tight ball. This formation happens with a bacterial genome and is called **supercoiling**. Whether DNA is packed using a complex arrangement (as in eukaryotes) or a supercoil (as in prokaryotes), nature has evolved different strategies to fit so much information into such a small space.

supercoiling the continuous twisting of prokaryotic DNA that reduces the volume of the DNA

Telomeres: A Key Difference

The structure of eukaryotic DNA presents another problem: DNA loss during replication. As you learned in Section 6.4, DNA polymerase produces small pieces of DNA (the Okazaki fragments) in the 5′ to 3′ direction of the lagging strand. The 5′ end of each Okazaki fragment is initially attached to an RNA primer (**Figure 4(a)**). The last Okazaki fragment on the lagging strand begins at the last RNA primer position, which is located close to, but not at, the end of the strand. Normally, the DNA being assembled as part of each following Okazaki fragment meets up with an RNA primer. DNA polymerase attaches to the end of the DNA fragment and then removes and replaces the RNA primer. However, this does not happen to the primer on the final Okazaki fragment, since no DNA is adjacent to the 5′ end. Instead, the RNA primer is removed but not replaced. Thus, no DNA is assembled on the lagging strand beyond the position of the last primer. Since the last sequence at the end of the parent strand is not copied, the final DNA is shorter by the amount of this uncopied segment (**Figure 4(b)**).



(a) during replication

(b) replication complete

Figure 4 (a) During replication, the last RNA primer on the lagging strand is positioned close to, but not at, the end of the chromosome. DNA polymerase is unable to synthesize the matching DNA at the end of the parent strand. (b) The last primer on the lagging strand is the only primer removed but not replaced by DNA polymerase. After replication is complete, this new chromosome loses DNA from one end. Note that the new chromosome that includes the other template strand loses DNA from the opposite end (not shown).

The loss of DNA during every cycle of replication causes chromosomes to continually shorten and can lead to the loss or damage of important genes. To prevent the loss of essential coding regions of DNA, zones of repetitive, non-coding sequences are found at the ends of eukaryotic chromosomes. These sequences are called **telomeres**. Every time that DNA replicates, part of its telomeres are lost, but the coding regions of DNA remain complete. Telomeres will be discussed in more detail in Section 6.6.

telomere a repeating sequence of DNA at the end of a chromosome that protects coding regions from being lost during replication

6.5 Review

Summary

- Cells store their genetic information in the form of chromosomes and plasmids.
- Eukaryotic chromosomes consist of DNA bound to histones. Together, the DNA and histones form nucleosomes, which are further wound and bundled into solenoids.
- Bacterial DNA is circular, lacks histones, and undergoes supercoiling to reduce its volume. Plasmids are small circular pieces of bacterial DNA. During conjugation, plasmids move from one bacterium to another.
- Telomeres are repeating sequences of DNA that are found on the ends of chromosomes. They prevent the loss of the coding regions of DNA during replication.

Questions

1. Place the following structures in order of size, from smallest to largest: solenoid, nucleosome, chromosome, histone. T/I
2. The nucleus of a certain cell measures 10 μm across, and a solenoid in the cell measures 30 nm across. How many solenoid structures could fit, side by side, in this nucleus? T/I
3. What enables DNA to wrap so tightly around a histone complex that it can conserve so much space? K/U
4. Use a t-chart or table to compare and contrast the DNA-packing strategies of bacteria and eukaryotes. List as many similarities and differences as you can. K/U C
5. Develop a hypothesis to explain why DNA replication in bacteria occurs in only one location, whereas in eukaryotes it occurs in many locations simultaneously. K/U T/I
6. Histones play an important role in the activation of genes. Do online research to learn how the methylation of histone proteins is used to turn genes on and off. 🌐 T/I
   (a) What is methylation?
   (b) How is this related to what are called the “tails” of histone proteins?
7. Histones help to protect DNA but are themselves proteins that are coded for by DNA. They can be defective if the corresponding DNA has a harmful mutation. Go online to find out what diseases are associated with defects in histone proteins. Would you expect such diseases to be serious? Why or why not? 🌐 T/I
8. Explain the benefits of having large non-coding regions at the ends of eukaryotic chromosomes. K/U T/I
9. Predict the impact of losing DNA in the telomere region throughout the organism’s life. K/U T/I

🌐 WEB LINK

DNA Replication and Aging

6.6

In electron micrographs of specially prepared chromosomes, telomeres appear like small dots at each end of the chromosomes (**Figure 1**). They act like aglets (the bits of plastic or metal at the ends of a shoelace) by capping off the ends of the chromosomes. This function is crucial to the life of a eukaryotic cell because telomeres protect the DNA from losing valuable coding information during replication. Although telomeres were once believed to be a chromosomal structure that did not change, we now know that their role is much more active. In fact, telomeres have several functions:

- They help to prevent chromosome ends from fusing to other chromosomes.
- They prevent DNA degradation from enzymes called nucleases.
- They assist DNA repair mechanisms in distinguishing DNA breaks from chromosomal ends.
- They may play a role in determining the number of times that a cell can divide, and therefore may play a critical role in determining the lifespan of an organism.

In this section, you will examine the role of telomeres in genetic continuity, their potential effect in the aging process, and their possible link to cancer.

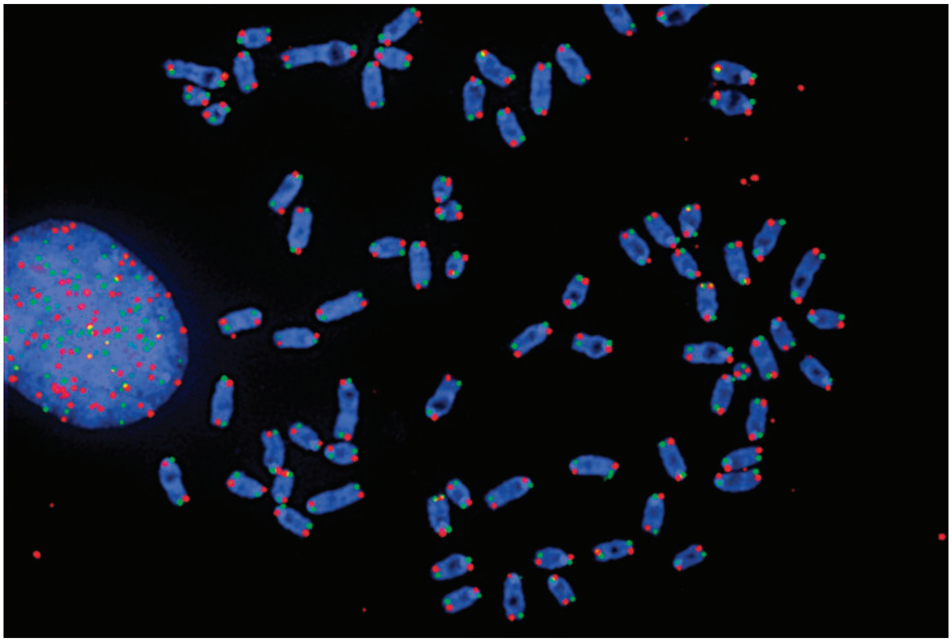


Figure 1 Fluorescently tagged telomeres of human chromosomes appear brightly coloured.

Role of Telomeres during Replication

Attached to the ends of DNA strands, telomeres are repeating sequences of nucleotides. For example, a common base code sequence found on the ends of one strand of DNA in human chromosomes (and the chromosomes of numerous other species) is 5′-TTAGGG-3′. In human chromosomes, this and similar sequences are repeated as many as 2000 times. Of course, the complementary strand has the sequence 3′-AATCCC-5′, repeated a matching number of times (**Figure 2**).

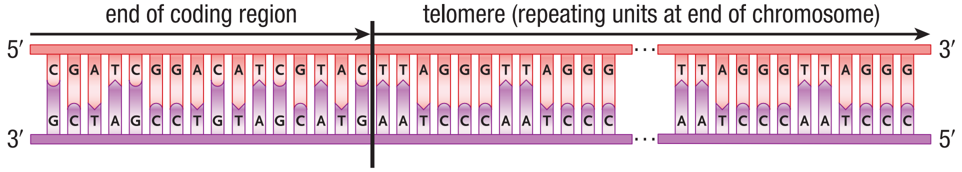

end of coding region
telomere (repeating units at end of chromosome)
5′
3′
C G A T C G G A C A T C G T A C T T A G G G T T A G G G
T T A G G G T T A G G G
G C T A G C C T G T A G C A T G A A T C C C A A T C C C
A A T C C C A A T C C C
3′
5′

Figure 2 Telomeres are repeating sequences of nucleotides at the ends of each chromosome.

As you learned in Section 6.5, not every portion of a chromosome is copied during replication. DNA polymerase I cannot replace the final RNA primer on the lagging strand and this, along with the non-terminal position of the last primer, results in the loss of small (uncopied) fragments of DNA from the ends of each chromosome after each replication process. If chromosomes were not capped by telomeres, a small portion of a gene near the end of a chromosome could be lost every time DNA replication occurred. Instead, only portions of the telomeres are lost, at a rate of about 100 base pairs per replication. The DNA that is inherited by new cells after mitosis is fully functional, with all its genes intact. The only difference, of course, is that the telomere portions of the chromosome are slightly shorter.

After many DNA replications (and the associated cell divisions), the telomeres are completely lost and therefore no longer provide protection for the chromosome. Essential portions of DNA may be lost during subsequent replications. As a result, a new cell may lose its ability to function properly. It may lose its ability to grow, metabolize, or divide. This period of decline, called **cell senescence**, may account for the loss of certain functions in individuals as they age. Thus, the telomeres are like a biological clock, counting down the total number of times that a cell can divide. This limit to cell division is known as the **Hayflick limit** (after Leonard Hayflick who discovered it in the 1960s).

cell senescence the period in a cell's lifespan when it loses the ability to divide and grow; often referred to as cell aging

Hayflick limit the total number of times that a normal cell can divide

The Hayflick limit is different for each species. In humans, a cell can divide roughly 50 times before its telomeres become too short (**Figure 3**). Although the Hayflick limit is different for different species, the length of a species' telomeres is not necessarily related to how long individuals of the species live. For example, a mouse's telomeres are longer than a human's.

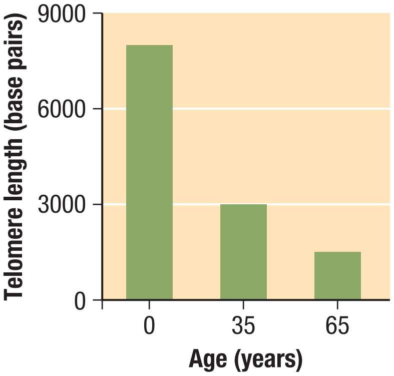


Figure 3 Telomere length decreases with age.

Germ line cells (which produce gametes) are unique because they must be able to continue replicating. They must maintain their genetic integrity from parent to offspring, generation after generation. These cells could not tolerate any loss of genetic material, even telomeres that would eventually run out and leave coding DNA at risk. In these germ line cells, an enzyme called **telomerase** adds more DNA to the shortening telomeres, continually restoring their length. Stem cells and certain white blood cells also show the presence of telomerase. CAREER LINK

telomerase an enzyme that adds new telomere sequences to the ends of chromosomes

Telomeres and Aging

The discovery of the role of telomeres and the Hayflick limit created major opportunities in the field of research on aging. The remaining length of the telomeres within a cell can tell us the age of the cell and how many more times the cell will be able to divide effectively. Although this is not the only factor that affects aging, it may play a role in how our bodies change as we get older.

Once a cell reaches its Hayflick limit and senescence begins, the cell's functioning begins to decline, effectively "aging" the same way that people do. Because not all cells in an organism reproduce at the same rate, an organism's cells undergo senescence at different times. As an organism ages, more of its cells reach senescence. This makes it more difficult for healthy cells to function at their optimum level.

You may recall Dolly, the cloned sheep. Dolly was born in July of 1996 and was hailed as the first mammal to be cloned from a mature somatic cell. The cell that was used was from a six-year-old donor, and the shortened length of the telomeres on its chromosomes reflected this. The expected lifespan of sheep of Dolly's breed is 11 to 12 years, but Dolly died at 6 years of age due to complications arising from progressive lung disease and severe arthritis. While it might seem logical to speculate that Dolly's short life was due to inheriting DNA with shorter telomeres, researchers were quick to point out that it is not unusual for normal sheep to die prematurely from the same conditions that Dolly had. The researchers that cloned Dolly could not find any evidence that Dolly's abnormalities were age related, nor has subsequent research shown a clear link between the age of donor cells and the lifespan of the clones produced.

Even though researchers have been unable to show a correlation between the length of the telomeres and life expectancy, entrepreneurs have exploited this idea to prey on modern society's search for a fountain of youth. Dietary supplements with claims to increase telomerase activity or decrease telomere degradation are becoming more and more common. In Europe, a home telomere measuring kit is easily available and may soon be found in your own neighbourhood drugstore. The secret to longer telomeres, however, may be as close as a hiking trail or health club. A decreased rate of telomere shortening, as well as increased telomerase activity, has been reported in some studies of people who exercise daily and eat properly balanced diets. On the other hand, shortened telomeres seem to be found more often in people who are obese or sedentary, or who smoke. Although research in this area is preliminary, it still seems safe to say that the secret to a longer life may simply be a healthy, active lifestyle.

Telomeres and Cancer: When Cells Do Not Age

Scientists who study the effects of aging can now investigate age-related illnesses at the cellular level. Evidence strongly links certain age-related diseases, such as atherosclerosis, dementia, and macular degeneration, to the senescence of specific cell groups in our bodies. However, the relationships between shortened telomeres and diseases are not clear. Understanding why our cells age can help researchers develop therapies to ease the damage caused by age-related diseases. A very special case of this type of telomere-related research is cancer research.

Cancer cells can be dangerous because they never stop dividing. Healthy cells use up the telomeres in their DNA over time and begin cell senescence, but cancer cells never do. This is because cancerous cells produce the enzyme telomerase in great quantities. The telomerase replaces the telomeres that are lost during cell division. As a result, the cancer cells are able to continue dividing indefinitely, making them effectively immortal. Such a growing mass of cancer cells can interfere with other cell groups or organs in the body and cause serious and often life-threatening diseases.

The knowledge of the role of telomerase has led to new therapies that target and inhibit the production of telomerase within cancer cells. In addition, decreasing the size of telomeres in potentially cancerous cells could act as a cancer prevention mechanism because it might cause the cells to die naturally before a mutation could cause them to become cancerous. However, when telomere lengths in some precancer cells become very short, the cells seem to be able to avoid death by increasing telomerase activity.

Such research, however, raises questions about the effects of using telomerase on otherwise healthy cells to prolong their natural life. For example, it is not known whether this would allow us to stay young indefinitely or give rise to new cancer cells. Much more research is needed before we can know, for certain, if telomerase therapies offer great potential. Understanding how genetic mechanisms, such as telomeres and telomerase, work is only one of the many challenges facing cancer specialists and gerontologists (scientists who study aging) today. CAREER LINK

UNIT TASK BOOKMARK

As you consider a topic for your Unit Task (p. 410), you might want to examine gene-based therapeutic approaches to preventing and treating cancer.

6.6 Review

Summary

- Telomeres protect chromosomes from losing essential coding DNA during replication. Once a chromosome's telomeres are gone, coding DNA is lost with every replication.
- The finite length of telomeres puts a limit on the number of times that DNA can successfully replicate and, consequently, on the number of times that a cell can divide. This is known as the Hayflick limit. Once a cell reaches its Hayflick limit, it begins a period of decline known as cell senescence.
- Cancer cells have an abundance of telomerase. This enzyme keeps their telomeres from shortening and makes them functionally immortal.
- Medical therapies that influence the activity of telomerase and alter the length of telomeres may prove effective in the treatment and prevention of some cancers and age-related diseases.

Questions

1. (a) How does the length of an individual's telomeres compare with the length of the telomeres of an older individual of the same species?
   (b) How does it compare with the length of the telomeres of an older individual of a different species? K/U
2. Why must telomerase activity take place in germ cells? K/U
3. Scientists are researching the effects of adding telomerase to healthy cells. What are some of the possible benefits of this therapy? What may be some negative effects? K/U T/I
4. Brainstorm possible ways in which the Hayflick limit benefits species. In other words, why do you think natural selection has favoured the evolution of such a limit to the number of cell divisions that can take place? T/I
5. While researching online, you find an advertisement for a product that claims it can reverse aging by increasing telomere length. Evaluate the validity of that claim. K/U T/I
6. A group of research oncologists want to try an experimental procedure on lab mice with cancer. They will inject medication that will decrease the length of the telomeres in the mouse cancer cells. Describe how this experimental procedure could help to treat the cancer. T/I
7. Cloning older organisms, such as Dolly the sheep, could greatly enhance the ability of scientists to grow organs for transplantation. However, using DNA from older cells presents a challenge for medical science. Explain why. K/U T/I
8. Using the Internet and other sources, research the average lifespan of several different organisms. What might this lifespan indicate about the rate at which each organism loses its telomeres? 🌐 T/I
9. Research and compare the relative lengths of the telomeres in the chromosomes of sperm, nerve, and skin cells in a 40-year-old human male. Summarize your findings. 🌐 T/I C

🌐 WEB LINK

CHAPTER 6 Investigations

Investigation 6.2.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Extracting DNA from Plants

The cells of different organisms contain different amounts of DNA. The size of the genome, the number of chromosomes, and the number of copies of each chromosome within a cell influence the amount of DNA that the cell contains. Determining the DNA content of a single cell is difficult. However, estimating the DNA content of a given mass of cells is possible. In this investigation, you will compare the amount of DNA extracted from different plant species.

Testable Question

Do all plant species contain the same amount of DNA per gram?

Prediction

Conduct online research to determine the somatic cell chromosome number for each plant species that you will use in this investigation. If possible, find the genome size in base pairs. Based on your findings, predict which plant species will contain the greatest amount of DNA per gram.

Variables

What are the dependent and independent variables in this investigation? Which variables are held constant?

Experimental Design

You will extract DNA from three plant species: strawberry, kiwi, and onion. You will dry the DNA and record its mass for each species. You will then calculate the percentage yield of DNA, per gram of original plant tissue, and compare this yield for the different samples.

Equipment and Materials

SKILLS HANDBOOK A1

- safety goggles
- lab apron
- rubber gloves
- balance
- mortar and pestle
- 4 large test tubes
- 3 graduated cylinders (10 mL)
- glass rod
- hot plate
- ring clamp
- utility stand
- thermometer
- 2 large beakers
- test-tube holder
- funnel
- 50 mL graduated cylinder
- forceps, hook, or paper clip
- strawberries
- 0.9 % w/v solution of sodium chloride, NaCl
- 10 % w/v solution of sodium dodecyl sulphate (SDS, or liquid soap)
- water
- ice
- cheesecloth or filter paper
- meat tenderizer solution 6 % w/v (3 g/50 mL of solution)
- 95 % ethanol (very cold)
- paper towels
- kiwis
- onions

To unplug the hot plate, pull on the plug, not on the cord.

Do not touch the top of the hot plate. It may be hot even if it does not appear to be hot.

If you are heating a beaker on the hot plate, make sure that you surround it with a ring clamp secured to a utility stand.

Alcohol is flammable. Make sure that there are no open flames nearby.

Procedure

SKILLS HANDBOOK A2.2

1. Put on your safety goggles, lab apron, and rubber gloves.
2. Obtain approximately 10 g of strawberries.
3. Place the strawberries in the mortar, and crush them using the pestle. This will separate and crush many of the cells, helping to expose the DNA.
4. Determine the mass of a large test tube. Transfer the crushed strawberries to the test tube, and determine the mass of the strawberries and test tube.
5. Add 10 mL of 0.9 % NaCl solution to the test tube. Mix well with a glass rod. Positive charges from Na^+ will neutralize the negative charges on the DNA, prevent the DNA molecules from repelling each other, and help to separate the DNA from the histone proteins.

6. Add 3 mL of 10 % SDS solution (soap), and mix thoroughly for 30 s with a glass rod. The soap will break down the plasma membranes, further exposing the DNA.
7. Place the test tube containing the mixture in a 60 °C hot-water bath for 10 min. The high temperature will break down the cell walls and cell membranes, and help to denature any enzymes that could degrade the DNA.
8. Using a test-tube holder, transfer the test tube into an ice-water bath for 5 min.
9. Strain the strawberry mixture through a piece of cheesecloth or filter paper, into a beaker, to remove any remaining solids.
10. Add an amount of meat tenderizer solution that is equal to half the volume of your filtrate. Swirl to mix. The meat tenderizer will break down any proteins that are still attached to the DNA.
11. Pour the mixture into a large test tube. Measure a volume of ice-cold ethanol that is twice the volume of your mixture. While holding the large test tube on a slant, very slowly pour the ethanol down the inside wall of the test tube. The alcohol will form a transparent layer on top of the mixture.
12. The DNA will begin to precipitate out of the mixture and aggregate where it contacts the chilled ethanol. It is a white, jelly-like substance. Using a glass rod, gently twirl the DNA that has precipitated out of the ethanol, and remove it from your mixture with forceps, a hook, or a bent paper clip.
13. Determine the mass of a small piece of paper towel. Place the jelly-like DNA extract on the paper towel to dry overnight.
14. Repeat Steps 1 to 13 with the kiwis and the onions.
15. Once the samples are dry, record the combined mass of the paper towel and DNA extract for each of the three samples. Determine the mass of the DNA extract.
16. Calculate the percentage yield of DNA from your original plant tissue samples.

Analyze and Evaluate

(a) What is the purpose of mashing up the strawberries, kiwis, and onions? T/I

(b) What proteins associated with DNA might be broken down by the meat tenderizer? K/U T/I

(c) Since DNA precipitates out in ethanol, is DNA soluble or insoluble in ethanol? Explain. T/I

(d) How could the haploid, diploid, or polyploid nature of the chromosomes of a plant affect the percentage yield of DNA? T/I

(e) Compare the percentage yield of DNA from the strawberry, kiwi, and onion tissue samples. Do your results support your prediction? Also compare your results with the number of chromosomes or genome size of each of these species. T/I

(f) Is the DNA that you extracted pure? Why or why not? If not, what other macromolecules might be present in your DNA sample? K/U T/I

(g) Provide additional reasons for a difference in the percentage yields of DNA for the three types of plant tissue. (You should conduct research, as well as providing your own reasons based on your observations). Hint: How would cell size or water content affect the DNA yield? 🌐 K/U T/I

Apply and Extend

(h) Research different plants and animals and find out the size of their genomes. Would you describe genomes as being relatively similar in size or highly variable? Support your answer with examples. 🌐 T/I C

(i) Would you expect fresh peas or dried peas to provide a higher yield of DNA per gram? Explain. T/I

(j) The amount of DNA can be better quantified by using a spectrophotometer. Research how a spectrophotometer works and how it can be used to determine the amount of DNA in a sample. 🌐 T/I

🌐 WEB LINK

Investigation 6.2.2 CONTROLLED EXPERIMENT

Extracting DNA: Design Your Own Experiment

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Testable Question

What effect does varying the experimental protocol have on the percentage yield of DNA extracted from strawberries?

Hypothesis

Formulate a hypothesis based on the testable question, after considering options for your experimental design.

Variables

As you design your experiment, carefully choose your independent and dependent variables and decide which variables need to be controlled.

Experimental Design

In this experiment, you will vary one of the steps in the procedure for Investigation 6.2.1 to determine the effect on the percentage yield of DNA.

Equipment and Materials

SKILLS HANDBOOK A1

Refer to the equipment and materials list in Investigation 6.2.1. Follow all the safety precautions in Investigation 6.2.1.

Procedure

SKILLS HANDBOOK A2.2

1. Choose the step in the procedure for Investigation 6.2.1 that will allow you to test your hypothesis. Write a detailed procedure that changes or eliminates this step. For example, you may wish to remove or alter the use of the salt, soap, or tenderizer solution or the hot-water or ice-water bath. Have your teacher approve your procedure.
2. Develop a data table to record your results.
3. Carry out your experiment to test your hypothesis.

Analyze and Evaluate

(a) How did your change to the procedure for Investigation 6.2.1 affect the experiment? Support your answer with your experimental results. T/I

(b) Do you think your change improved the experimental protocol? Why or why not? T/I

Apply and Extend

(c) Why would a research scientist want to manipulate an experimental procedure? T/I

(d) Conduct research on other experimental procedures used to extract DNA. Discuss their similarities and differences. For example, compare DNA extraction from plants to extraction from animals. T/I

WEB LINK

Investigation 6.4.1 ACTIVITY

Role-Playing DNA Replication

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

In this activity, you will demonstrate your knowledge and understanding of DNA replication by designing a role play with some of your classmates.

Purpose

To design a role play that illustrates the process of DNA replication

Procedure

1. Form a group of four to six students.
2. On a piece of chart paper, summarize the process of DNA replication. Include the key enzymes, as well as the DNA molecule.
3. Design a role play that will illustrate DNA replication. Think of any props or materials you will need to help your audience understand your role play. Consider how you will represent the individual DNA strands and their bases. How might you illustrate the orientation of each strand? How will your audience differentiate between the different enzymes?
4. Write a loose script for your role play. Make sure that all the members of your group are included. Act out your role play.

Analyze and Evaluate

(a) How did you represent each enzyme or macromolecule in your role play? T/I

(b) What challenges did you face while illustrating DNA replication in your role play? T/I

(c) If you repeated this activity, how would you improve your role play? T/I

(d) List two ideas or processes that have now become clearer to you after completing this activity. T/I

Apply and Extend

(e) Go online to view one or more DNA replication animations. After watching the animation(s), what would you change in your role play? T/I C

(f) List any questions you still have about the process of DNA replication. T/I C

WEB LINK

CHAPTER 6 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts on page 268. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, and general equations.
2. Look back at the Starting Points questions on page 268. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

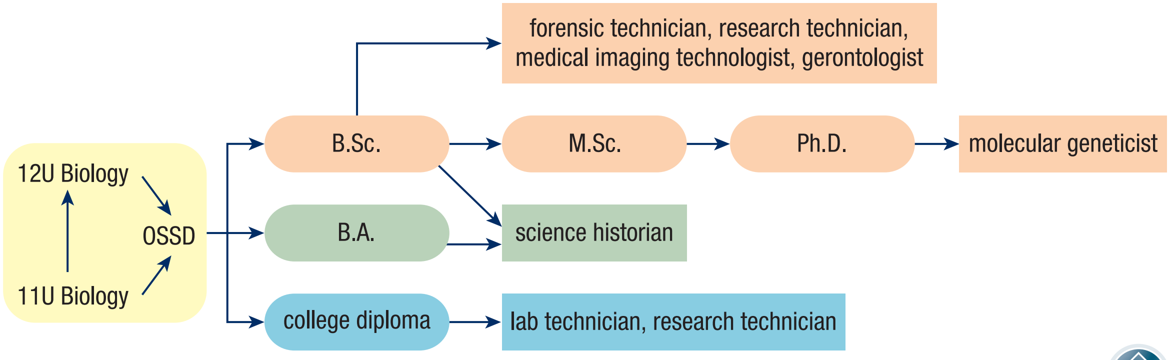
histone (p. 271)
plasmid (p. 271)
genome (p. 271)
transformation (p. 274)
bacteriophage (p. 275)
purine (p. 276)
pyrimidine (p. 276)
complementary base pairing (p. 278)
semiconservative replication (p. 282)
replication origin (p. 283)
helicase (p. 283)
replication fork (p. 283)
topoisomerases (p. 284)
single-strand binding protein (SSB) (p. 284)
replication bubble (p. 284)
nucleoside triphosphate (p. 285)
RNA primase (p. 286)
RNA primer (p. 286)
DNA polymerase III (p. 286)
leading strand (p. 286)
lagging strand (p. 286)
Okazaki fragment (p. 286)
DNA polymerase I (p. 286)
DNA ligase (p. 286)
DNA polymerase II (p. 286)
nucleosome (p. 291)
solenoid (p. 291)
supercoiling (p. 293)
telomere (p. 293)
cell senescence (p. 296)
Hayflick limit (p. 296)
telomerase (p. 296)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to DNA and molecular genetics that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.


forensic technician, research technician, medical imaging technologist, gerontologist
12U Biology
OSSD
11U Biology
B.Sc.
M.Sc.
Ph.D.
molecular geneticist
B.A.
science historian
college diploma
lab technician, research technician

CAREER LINK

CHAPTER 6 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. According to Mendel, which of the following cause an organism's size, colour, and markings? (6.1) K/U
   (a) chromosomes
   (b) genes
   (c) alleles
   (d) factors
2. Which term is associated with eukaryotic DNA? (6.1) K/U
   (a) chromosome
   (b) histone
   (c) telomere
   (d) all of the above
3. If 28 % of a segment of DNA is composed of guanine, how much of the segment is adenine? (6.2) K/U
   (a) 7 %
   (b) 22 %
   (c) 28 %
   (d) There is no way to determine this.
4. How did the work of Franklin and Wilkins contribute to the discovery of the structure of DNA? (6.2) K/U
   (a) They determined the rule of base pairing.
   (b) They determined that DNA has an X-shape.
   (c) They determined the double helix structure.
   (d) They determined that the strands run antiparallel.
5. Which of these findings made Watson and Crick confident that their DNA model was correct? (6.3) K/U
   (a) Chargaff's base-pairing ratios
   (b) Pauling's three-strand model
   (c) Franklin's early disagreement with the double helix theory
   (d) all of the above
6. What would have been the result of Meselson and Stahl's experiment if DNA had undergone conservative replication? (6.4) K/U
   (a) one band containing only ^{14}N
   (b) one band containing only ^{15}N
   (c) two bands: one of ^{15}N and one of ^{14}N
   (d) three bands: one of ^{15}N, one of ^{14}N, and one of 1:1 ^{14}N:^{15}N
7. Which characteristic of the structure of DNA results in a lagging strand and a leading strand during DNA replication? (6.4) K/U
   (a) its phosphate backbone
   (b) its antiparallel strands
   (c) the ratio of purines to pyrimidines
   (d) the full twist every 10 nucleotides
8. What is the function of DNA ligase in replication? (6.4) K/U
   (a) It initiates a replication bubble.
   (b) It prevents DNA strands from tangling.
   (c) It places nucleotides to form a new DNA strand.
   (d) It fills gaps on the lagging strand.
9. Which method do prokaryotes use to compact DNA? (6.5) K/U
   (a) spooling around a histone
   (b) forming a nucleosome
   (c) supercoiling
   (d) winding into solenoids
10. Where are telomeres located? (6.6) K/U
    (a) at the ends of chromosomes
    (b) on the leading strand
    (c) at the replication fork
    (d) on prokaryotic plasmids
11. What does the Hayflick limit restrict? (6.6) K/U
    (a) number of coils around a histone
    (b) number of times that a cell can divide
    (c) number of Okazaki fragments on the lagging strand
    (d) number of nucleotides in a telomere

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

12. Eubacteria have histone-like proteins associated with their DNA. (6.1) K/U
13. The number of chromosomes that a species has is proportional to the size and complexity of the species. (6.1) K/U
14. The work of Hershey and Chase proved that DNA is the carrier of genetic material. (6.2) K/U
15. Watson and Crick are credited with discovering the structure of DNA, although many scientists contributed to their discovery. (6.3) K/U
16. During the first step of DNA replication, DNA polymerase unwinds the DNA strands. (6.4) K/U
17. Histones, nucleosomes, and solenoids are all structures that help to compact DNA into the nucleus of a cell. (6.5) K/U
18. Telomeres prevent essential coding sequences of DNA from being replicated. (6.6) K/U
19. Newborns experience more cell senescence than adults. (6.6) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 6 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which term best describes Mendel's "heredity factor"? (6.1) K/U
   (a) DNA
   (b) RNA
   (c) alleles
   (d) genes
2. What cellular product does an individual gene code for? (6.1) K/U
   (a) carbohydrate
   (b) enzyme
   (c) final protein
   (d) polypeptide
3. Which organelle is directly involved with translating DNA into a protein? (6.1) K/U
   (a) nucleus
   (b) ribosome
   (c) mitochondrion
   (d) chromosome
4. Before DNA was discovered, what did most scientists believe carried the information for inherited traits? (6.2) K/U
   (a) RNA
   (b) amino acids
   (c) proteins
   (d) bacteria
5. What did Edward Chargaff's experiments reveal about DNA? (6.2) K/U
   (a) DNA is the genetic material.
   (b) Bases occur in definite ratios in double-stranded DNA.
   (c) There is a material that can transform bacteria.
   (d) X-rays can be used to find the shape of DNA.
6. What does each nucleotide contain? (6.2) K/U
   (a) nitrogen base
   (b) phosphate group
   (c) five-carbon sugar
   (d) all of the above
7. Which statement about DNA replication is correct? (6.2) K/U
   (a) New DNA molecules are synthesized using short sequences of nucleotides from both old and new strands.
   (b) New DNA molecules are synthesized by producing a new complementary strand on an original template strand.
   (c) A new DNA molecule is produced when two new strands are combined.
   (d) none of the above
8. Which part of Pauling and Corey's model of DNA was not included in Watson and Crick's model? (6.3) K/U
   (a) Phosphate groups are on the inside of the molecule.
   (b) The strands run antiparallel.
   (c) The helix makes a full twist every 10 nucleotides.
   (d) The DNA molecule has two strands.
9. Referring to the original DNA strands, in which direction does DNA replication occur? (6.4) K/U
   (a) from 5′ toward 3′ for both strands
   (b) from 3′ toward 5′ for both strands
   (c) from 5′ toward 3′ for the lagging strand only
   (d) from 3′ toward 5′ for the leading strand only
10. What role do topoisomerases play in replication? (6.4) K/U
   (a) They initiate DNA replication.
   (b) They build a new strand from the template.
   (c) They ensure that the DNA strand is positioned correctly for replication.
   (d) They relieve tension in the DNA molecule.
11. What is a histone? (6.5) K/U
   (a) group of amino acids
   (b) prokaryotic DNA
   (c) positively charged protein
   (d) eukaryotic organelle
12. How does the structure of prokaryotic DNA differ from the structure of eukaryotic DNA? (6.5) K/U
   (a) Prokaryotic DNA can be circular.
   (b) Eukaryotic DNA is stored in the nucleus.
   (c) DNA plasmids exist in prokaryotes.
   (d) all of the above
13. What happens when telomeres become too short? (6.6) K/U
   (a) Coding regions of DNA are lost.
   (b) Cell division stops immediately.
   (c) New telomeres are formed.
   (d) The cell begins to divide uncontrollably.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

14. Bacteria possess membrane-bound organelles to store their DNA. (6.1) K/U
15. Purines pair with purines, and pyrimidines pair with pyrimidines. (6.2) K/U
16. Hershey and Chase helped to confirm that DNA is the genetic material in living things by conducting a series of experiments in which they traced radioactive phosphorus in DNA from viruses into bacteria. (6.2) K/U

17. Watson and Crick had to convince many other scientists that their double helix model was correct. (6.3) K/U

18. During DNA replication, Okazaki fragments form on both the leading and lagging strands of DNA. (6.4) K/U

19. After the addition of a primer to a DNA strand, DNA polymerase I builds in the 3′ → 5′ direction on both strands. (6.4) K/U

20. DNA replication is described as conservative. (6.4) K/U

21. Centromeres are repeating sequences of DNA at the ends of a chromosome that help to protect the coding regions of the DNA. (6.5) K/U

22. Okazaki fragments on the lagging strand of DNA cause the copied DNA to be longer than the parental strand. (6.5) K/U

23. Prokaryotic DNA undergoes supercoiling to reduce its volume. (6.5) K/U

Match each term on the left with the most appropriate description on the right.

24.	(a) histone	(i) region of a cell where looped DNA is found
	(b) plasmid	(ii) protein used for DNA coiling
	(c) nucleoid	(iii) circular DNA that is found in bacteria
	(d) chromatin	(iv) bundled coils of condensed DNA (6.1, 6.2) K/U
25.	(a) Gregor Mendel	(i) used strains of bacteria to develop the transforming principle
	(b) Watson and Crick	(ii) proposed that a “hereditary factor” is responsible for passing traits from parents to offspring
	(c) Hershey and Chase	(iii) used radioactive sulfur and phosphorus to determine that DNA is the genetic material in living things
	(d) Frederick Griffith	(iv) amassed information from other scientists’ investigations to propose the double helix model of the structure of DNA (6.1, 6.2, 6.3) K/U
26.	(a) DNA ligase	(i) seals the gaps between Okazaki fragments
	(b) DNA polymerase	(ii) assembles nucleotides to build new DNA strands on template strands
	(c) helicase	(iii) places primers on the template strand
	(d) RNA primase	(iv) unravels a DNA strand to begin replication (6.4) K/U

Write a short answer to each question.

27. In your notebook, identify and briefly describe each labelled structure shown in **Figure 1**. (6.1, 6.2) K/U C

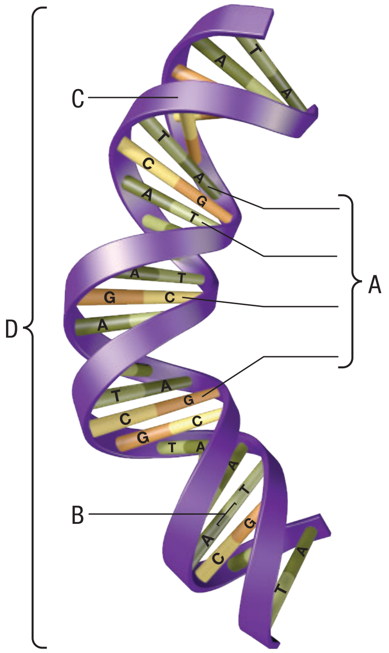


Figure 1

28. (a) Briefly describe the findings that led Griffith to discover transformation in bacteria.
    (b) What was the significance of his findings? (6.2) K/U

29. A template strand of DNA contains nucleotides in the following proportions: 14 % adenine (A), 33 % thymine (T), 21 % cytosine (C), and 32 % guanine (G). What can you expect the proportions of the nucleotides to be in the newly formed complementary strand? (6.2) K/U T/I

30. How did the use of technology contribute to Watson and Crick’s discovery of the double helix structure of DNA? (6.3) K/U

31. Describe the two roles of DNA polymerases in replication. (6.4) K/U

32. Explain the role of positive and negative charges in packing eukaryotic DNA. (6.5) K/U

33. Why are plasmids important in genetic engineering? (6.5) K/U

34. A normal human cell can divide only about 50 times. What limits the cell’s ability to replicate past 50 cell divisions? (6.6) K/U

Understanding

35. Explain why proteins cannot be directly synthesized from DNA. (6.1) K/U

36. How did Avery, McLeod, and McCarty isolate DNA as the molecule that had caused transformation in Griffith’s experiment? (6.2) K/U T/I

37. (a) Explain why DNA is classified as a polymer.
    (b) What are the monomers that make up this polymer? (6.2) K/U

38. Using a timeline, list the major experiments that led to the discovery of DNA as the molecule of heredity. (6.2) K/U C

39. Identify the factors that give DNA its symmetry. (6.2) K/U

40. Refer to the diagram of DNA replication in **Figure 2**. (6.4) K/U
    (a) Identify the letter(s) indicating the 3′ end(s) of the molecules.
    (b) Identify the letter(s) indicating the 5′ end(s).
    (c) Explain your reasoning for your answers in (a) and (b).

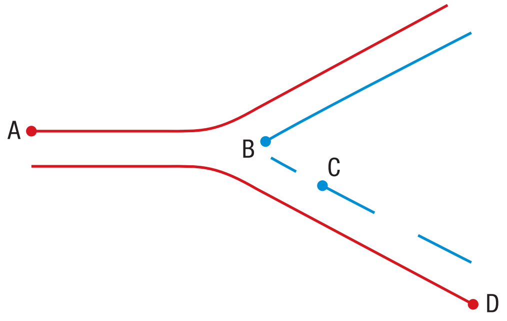


Figure 2

41. How does bonding between the nitrogenous bases compare to bonding between the nucleotides of the backbone? (6.2, 6.4) K/U

42. Describe how the structure of DNA allows it to be easily replicated. (6.4) K/U A

43. If a cell were damaged and DNA ligase could no longer be produced, how would replication be affected? (6.4) K/U A

44. Identify and describe a common error that occurs during DNA replication. (6.4) K/U

45. In physics, a solenoid refers to a thin wire that is wrapped around a metal core, as shown in **Figure 3**. Explain why a cellular solenoid has the same name as this structure. (6.5) K/U A

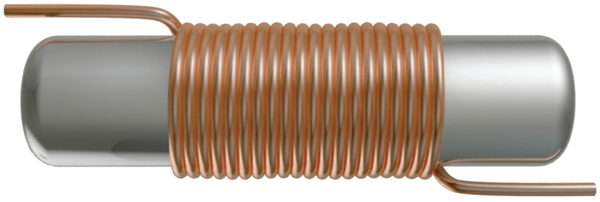


Figure 3

46. Identify the pink structures shown in **Figure 4**. Describe their function. (6.5, 6.6) K/U

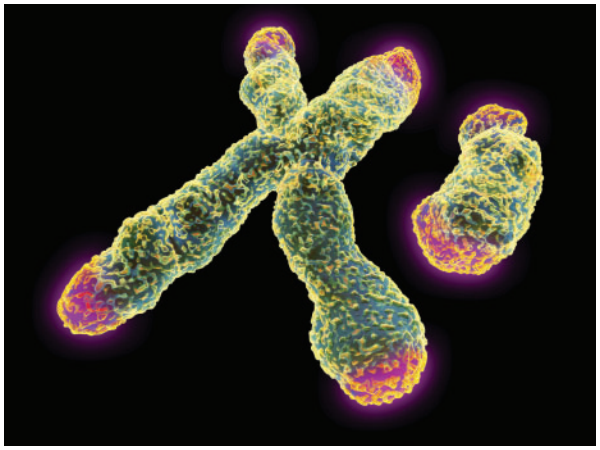


Figure 4

47. A cell is exposed to a toxic chemical that attacks and destroys telomeres. How will DNA replication be affected? (6.6) K/U T/I

Analysis and Application

48. The average length of a nucleotide is 0.34×10^{-9} m, and there are 6×10^{9} base pairs in a human diploid cell. If there are approximately 5.0×10^{13} cells in a mature human and the distance to the Sun is approximately 1.5×10^{11} m, determine how many times the DNA from one human could reach the Sun and return. (6.1) T/I

49. A molecule of DNA was found to have 24 % cytosine. Determine the percentage of each nitrogenous base in the molecule of DNA. (6.2) K/U T/I

50. In a double helix DNA molecule, there is a complete turn every 3.4 nm, or every 10 nucleotides. (6.2) T/I
    (a) If a DNA molecule contained 170 million base pairs, how long would it be? Show your work.
    (b) How many complete turns of the double helix would exist in this DNA molecule? Show your work.

51. Assume that the DNA molecule in a particular chromosome is 75 mm long. (6.2) T/I
    (a) How many nucleotide pairs does this molecule have? Show your work.
    (b) How many nitrogenous bases does this molecule have? Show your work.

52. **Table 1** presents the nucleotide base composition of the DNA obtained from three different organisms. Examine the data in Table 1. Given your knowledge of DNA structure and base composition distribution, why is it necessary for the $\frac{A + G}{C + T}$ percentage to equal 1.00 and yet not necessary for the $\frac{A + T}{G + C}$ percentage to equal 1.00? (6.2) K/U T/I

Table 1

Source	A	T	G	C	$\frac{A + T}{G + C}$	$\frac{A + G}{C + T}$
mouse	29.1	29.0	21.1	21.1	1.38	1.00
corn	25.6	25.3	24.5	24.6	1.04	1.00
frog	26.3	26.4	23.5	23.8	1.11	1.00

Note: All quantities are percents (%).

53. Recall Frederick Griffith's experiment with R-strain and S-strain bacteria in mice. In his fourth trial, he mixed the heat-killed S-strain cells with live R-strain cells and injected them into mice. The mice died. This led Griffith to develop his idea of transformation. After further investigation, Griffith found that a blood sample from the dead mice showed living S-strain bacteria. Griffith was able to reproduce these cells and produce even more S-strain cells. Explain how Griffith's discovery ruled out the possibility that the live R-strain cells just used the capsules of the dead S-strain cells to become infectious. (6.2) K/U T/I

54. **Figure 5** shows a short section of a DNA molecule. (6.2) K/U T/I C
   (a) Sketch Figure 5 in your notebook, and label the 5′ and the 3′ ends.
   (b) What information did you use to determine the 5′ and 3′ ends of the DNA molecule?

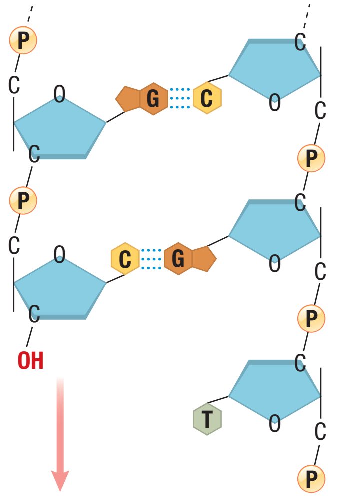


Figure 5

55. While working on the structure of the DNA molecule, James Watson and Francis Crick originally proposed that purines were bonded to purines and pyrimidines were bonded to pyrimidines. (6.2, 6.3) K/U T/I
   (a) Explain why their proposed model did not fit the observations made by Edward Chargaff.
   (b) How did their model also contradict Franklin and Wilkins's X-ray crystallography results from DNA?

56. How did the discovery of the molecular structure of DNA illustrate the importance of communication among scientists? (6.3) K/U A

57. Technology is important to most scientific investigations. Often, as technology improves, scientists acquire the tools they need to make previously unattainable discoveries. Prepare a one-paragraph summary of the role of each of the following technologies in the experiments that led to the discovery of DNA as the genetic material and the structure of DNA. (6.2, 6.3, 6.4) K/U C
   (a) centrifuge
   (b) X-ray crystallography
   (c) radiation detection

58. Franklin's crystallography led her to conclude that DNA was a double helix, the sugar-phosphate backbone was on the outside of the DNA molecule, and the distance between the two backbones of the DNA strands was equal along the entire length of the molecule. However, Franklin could not determine how the bases bonded in the middle. How did Watson and Crick use the available information about the nitrogenous bases to determine the structure of the DNA molecule? (6.3) K/U T/I

59. The replication of a complete genome in humans and some bacteria takes roughly the same amount of time, despite some major differences. Answer the following questions, showing all your work. (6.4) K/U T/I
   (a) The DNA of *E. coli* has approximately 4.6×10^6 base pairs (bp). If it can replicate at a rate of 1000 bp/s, how long would it take to replicate its genome?
   (b) The DNA in a human cell has 150×10^6 bp and can replicate at a rate of 50 bp/s. If this was the overall replication rate, how long would it take to replicate a human genome?
   (c) In humans, this replication process actually takes less than an hour. Why is it much faster than you predicted?

60. Use a graphic organizer of your choice to compare and contrast DNA replication with photocopying a document. (6.4) T/I C

61. Suppose that you are working in a laboratory and are responsible for replicating DNA fragments. You have been given a mixture that contains a series of single-stranded DNA fragments, all four nucleoside triphosphates, and DNA polymerase III. (6.4) K/U T/I
    (a) What else needs to be added to ensure DNA replication?
    (b) Would any replication forks exist? Would any Okazaki fragments exist? Explain.
62. Ultraviolet rays from the Sun can initiate chemical changes in the nitrogenous bases of DNA. These chemical changes may result in errors during replication. (6.4) T/I
    (a) Predict the errors that may result from exposure to UV rays.
    (b) Explain the mechanisms that the cell employs to combat the damage caused by UV rays.
    (c) Describe the part of the body that is most at risk for cellular DNA damage, and explain why.
63. Recognizing specific chemical arrangements is important at many levels in living things, including the molecular level, cellular level, and organism level. Describe three situations in which recognizing specific chemical arrangements is necessary at the genetic level. (6.4) T/I A
64. DNA replication in a eukaryotic cell is initiated at many points along the DNA strand. Because of this, replication can occur at all of these points simultaneously. **Figure 6** shows a replication bubble. Explain how each DNA template strand can be both a leading strand and a lagging strand at the same time. (6.4) K/U T/I

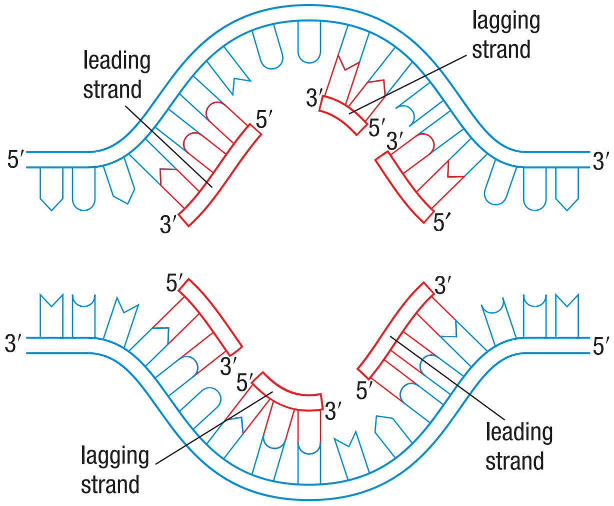


Figure 6

65. Use a flow chart to sequence the steps of DNA replication that involve the following enzymes: DNA polymerase III, DNA ligase, helicase, RNA primase, and DNA polymerase I. In your flow chart, describe what happens at each step and the role of the enzyme in this step. (6.4) K/U C
66. A geneticist isolates and purifies molecules that are required for DNA replication. She adds DNA to the mixture and then waits to check the results. She finds that replication took place, but the new molecules consist of a normal strand paired with many short, separate segments of nucleotides. Use a diagram and a paragraph to explain the geneticist's results. (6.4) K/U T/I C A
67. A scientist wants to find the cause of a cellular disease so it can be treated. The scientist has compiled a group of patients and collected data on the degree of incidence of the disease in the cells of these patients. A graph of the results is shown in **Figure 7**. Using the data in the graph, develop a hypothesis about what causes the disease. (6.6) K/U T/I

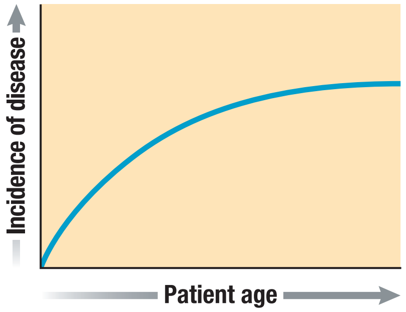


Figure 7

Evaluation

68. Imagine that you are a scientist who is studying a bacteria-like life form from another planet. You notice that it has six different bases: R, S, T, X, Y, and Z. The bases R, S, and T are always in the same proportion. Similarly, the bases X, Y, and Z are always in the same proportion. Propose a reasonable hypothesis about the structure of the nucleic acid. (6.2) K/U T/I
69. Several of the molecules and enzymes that are involved in DNA replication are also useful to genetic engineers for making recombinant DNA. Identify three molecules in prokaryotic or eukaryotic cells that would be useful to genetic engineers who are working with recombinant DNA technology, and explain why. (6.2, 6.4, 6.5) T/I A
70. Studies have shown that the topoisomerase enzymes involved in eukaryotic DNA replication are also involved with supercoiling DNA in prokaryotic cells. Why might these enzymes, in particular, be involved with prokaryotic supercoiling? (6.4, 6.5) K/U T/I A

71. Eukaryotes differ from prokaryotes in that each chromosome has more than one replication site. Hypothesize why this is the case. (6.5) K/U T/I

72. Tortoise carapaces, such as those shown in **Figure 8**, are an inherited characteristic. What does this suggest about the relationship between the characteristic and the animals' DNA? How might a scientist try to determine the sequence of base pairs in the portions of DNA responsible for this feature? (6.6) K/U T/I

Figure 8

73. The non-coding region of DNA that makes up the telomere has a repeating sequence of nucleotides. In humans, the repeating sequence is usually six or seven base pairs long and has very few Cs on one strand. The sequence GGGTTAA is a typical example. Other species have different repeating sequences. Suggest a possible benefit for the nucleotide sequence of the telomere to be a repeating sequence. (6.4, 6.5, 6.6) K/U A

Reflect on Your Learning

74. DNA and its processes have been compared with an assembly manual for a machine. Based on what you have learned in this chapter, create your own analogy about DNA. For example, you could create an analogy about how DNA resembles a poem. Include as many aspects of the structure of DNA and the processes it undergoes as possible. T/I C A

75. "The development of a scientific theory or model requires the work of many scientists over time." Discuss this statement, using your knowledge about the development of the model of the DNA molecule. T/I C

76. "It is not only the pieces of the puzzle that matter, but also how they fit together." This statement played an important role in the determination of the structure of DNA. Looking back on the chapter, how is this statement true? T/I C

77. You have learned about mechanisms that ensure that the activities of a living cell run smoothly. Which mechanism interests you the most? What questions has this mechanism led you to think about? K/U C

78. You have learned that the length of a telomere decreases with each DNA replication. Germ cells, stem cells, and some white blood cells contain the enzyme telomerase, which adds nucleotides to the telomeres. If a safe medical treatment became available to increase the level of telomerase in your cells, would you use it? In the format of a letter to the editor, explain why people might or might not want this treatment. What are its benefits and risks to individuals, to society, and to the planet? T/I C A

Research

WEB LINK

79. DNA polymerase is a large group of proteins. It plays an important role in DNA replication. Friedreich's ataxia, a disease associated with DNA polymerase, is caused by DNA slippage during replication. Use Internet sources to answer the following questions: T/I C
    (a) Research the various types of DNA polymerase, and summarize their role in DNA replication.
    (b) What is DNA slippage?
    (c) What are the effects of Friedreich's ataxia?

80. Watson and Crick are best known for their role in determining the structure of DNA. Conduct online research and develop a multimedia overview of what Watson and Crick studied following their DNA work. How has their later work improved our understanding of our world? T/I C

81. DNA repair is an important process in the cell. Create a short multimedia production that uses the following guiding questions to highlight the important aspects of DNA repair in eukaryotes:
    - What steps are involved in the process of DNA repair?
    - What enzymes are responsible for DNA repair?
    - What types of diseases are associated with DNA repair disorders?
    - What are the symptoms of six diseases associated with DNA repair disorders? K/U T/I C

82. Scientists are researching the possibility of using telomerase inhibitors to kill cancer cells. Research and gather the information you would need if you were asked to prepare a pamphlet as part of a campaign to raise money for this research. Include the following information in your pamphlet:
    - the activity of telomerase in cancer cells
    - how telomerase concentrations change in cells over time
    - current research into telomerase and its role in cancer T/I C

CHAPTER

7 Genes and Protein Synthesis

KEY CONCEPTS

After completing this chapter you will be able to

- explain how DNA is transcribed in the nucleus of a cell into a primary RNA transcript by RNA polymerase
- discuss how the primary RNA transcript is processed to become mature mRNA
- describe what enables mRNA to exit the nucleus and explain how it is translated into a polypeptide with the help of tRNA, amino acids, ATP, and ribosomal subunits
- compare the processes that control protein synthesis in prokaryotes with the processes in eukaryotes
- discuss how mutations may arise and lead to changes in protein structure and function
- define genetic expression, and explain factors that control the expression of genes
- discuss how the form and behaviour of the genetic material in viruses make viruses suitable as a tool in genetic engineering

How Are Proteins Produced by the Cell?

The cells in an organism's body synthesize approximately 100 000 different proteins. Some of these proteins are produced in all cells throughout the organism's lifetime, while others are only produced at certain times and/or in certain types of cells. In an animal, for example, digestive enzymes and structural proteins are produced in huge quantities. Other proteins, such as hormones, are produced only in small amounts.

Recall that the building blocks of proteins are 20 amino acids. Some amino acids are acquired from your diet, while others are synthesized in your cells. The number of amino acids and their sequence differentiate proteins from each other. For example, collagen is very different from insulin, and insulin is very different from hemoglobin. As a result, each protein has a very specific function.

But how are these proteins made? How does the cell know the sequence of amino acids in order to assemble each one accurately? This information is stored in the DNA, in the sequences of the four nucleotide bases: adenine (A), thymine (T), cytosine (C), and guanine (G). The human genome contains more than 20 000 genes and yet the genetic code is based on only these four nucleotide bases. Furthermore, these 20 000 genes code for 100 000 different proteins.

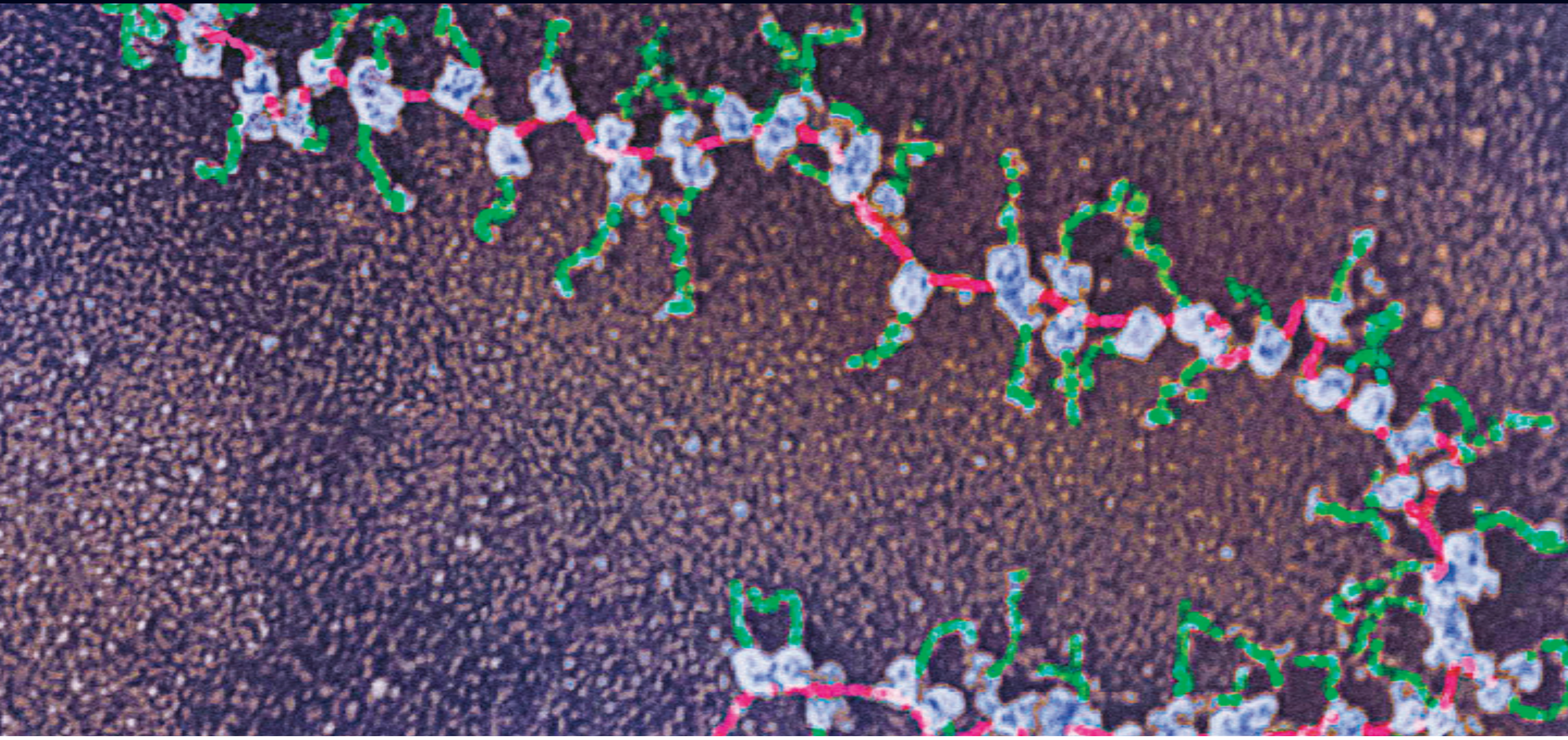
Recall that the message code originates in the nucleus, which houses the coded information: DNA. The genes are different combinations of the four nucleotide bases along the length of the DNA strands. Messages from the genes, in the form of RNA molecules, travel to the ribosomes to direct the assembly of the proteins. Variations in the copying and editing of the messages culminate in the assembly of the many different proteins by the ribosomes.

In this chapter, you will examine the interactions between DNA, RNA, organelles, and amino acids that result in the production of proteins. For example, on the facing page, the process of translation in a salivary gland cell of a midge is shown. Ribosomes (blue) attach to the messenger RNA strand (pink) and read its code. As the ribosomes move along the mRNA, a polypeptide (green) grows from each ribosome. In addition, you will learn the mechanisms used by cells to regulate the production of proteins and the types of mutations that may occur.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Based on what you have learned about protein tertiary and quaternary structure, suggest ways in which 10 different polypeptides could be used to assemble more than 10 different proteins.
2. What is the "missing link" between DNA and protein?
3. Before Watson and Crick identified the structure of DNA, why did other scientists question its function as the genetic code?
4. Given that mutations cause changes in DNA sequences, how might such changes manifest themselves in the structure of proteins?



Mini Investigation

Breaking the Code

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

DNA is composed of four nucleotides: adenine, thymine, cytosine, and guanine. The sequence of the nucleotides in a gene dictates the sequence that is used by a ribosome to assemble the amino acids in a protein. In this investigation, you will simulate the process that takes place in eukaryotic cells to build a protein using the instructions found in a DNA sequence. You will assemble a string of three nucleotides that will code for an amino acid (represented by a word). Several of these nucleotide strings, when put together, will create a protein (represented by a meaningful sentence).

Materials: DNA code

1. Your classroom represents one cell. Go to the nucleus of the cell (an area designated by your teacher). Obtain a DNA sequence from your teacher. This DNA sequence represents a gene.
2. While in the nucleus, rewrite the DNA as an RNA coded message. Remember that RNA is complementary to DNA, with the exception of thymine. RNA contains uracil rather than thymine. Your RNA strand is the key to deciphering the DNA sequence.
3. Exit the nucleus, and go to your desk (the ribosome).
4. Separate your RNA strand into groups of three consecutive bases. Each group of three bases codes for an amino acid (a word). On the board, find the word associated with each of your groups of three bases. Copy the word under each group.
5. Compile your protein (a sentence). If your sentence does not make sense, then the original DNA sequence must have contained a mutation leading to an error.

A. Share your sentence with a classmate. What kind of molecule does your sentence represent? T/I

B. Why did you have to build a complementary RNA strand to your DNA in the area of the classroom that represented the nucleus? T/I

C. Each student desk represents a ribosome. Is this an accurate representation, based on cell structure? T/I

D. What does each word represent in terms of protein synthesis? T/I

E. One part of the simulation represents transcribing, and the other part represents translating. Which is which? T/I

7.1 From Gene to Protein

As you learned in Section 6.1, Gregor Mendel experimented with garden peas and laid the foundation for the science of genetics. His experimental results led to his hypothesis that certain factors are responsible for the patterns of inheritance that he observed in his pea plants. He proposed that the height of the pea plant, the colour of the flower, and the shape and colour of the seed are determined by these factors, which are passed from parent to offspring. These factors are now known as genes. They direct the production of proteins that determine the physical characteristics of organisms. They also direct the production of other essential proteins, such as antibodies, enzymes, and hormones. Proteins drive cellular processes (such as metabolism), determine physical characteristics, and manifest genetic disorders by their absence or by their presence in an altered form.

One Gene–One Polypeptide Hypothesis

Two key pieces of research, involving defects in metabolism, led scientists to the discovery of how genes encode for proteins (or, in other words, specify the amino acid sequence). The first piece of research began in 1896 with Archibald Garrod, an English physician. He studied alkaptonuria, a human disease that is detected easily because a patient's urine turns black in air. Garrod studied families of these patients and concluded that alkaptonuria is an inherited trait. He found that people with alkaptonuria excrete a particular chemical in their urine. Garrod concluded that people without the disease are able to break down the chemical, whereas people with alkaptonuria cannot. By 1908, Garrod had concluded that the disease was an "inborn error of metabolism." Later research has shown that alkaptonuria is caused by a mutation of a gene that normally codes for an enzyme that breaks down the amino acid tyrosine. The altered gene codes for a defective enzyme that cannot fully break down tyrosine. When tyrosine is not broken down fully, a chemical known as alkapton accumulates. Alkapton turns black in air. Garrod's work was the first to show a specific relationship between genes and metabolism.

The second piece of research that led scientists to the gene–protein connection was conducted by George Beadle and Edward Tatum in the 1940s. Working with the orange bread mould *Neurospora crassa*, they collected data that showed a direct relationship between genes and enzymes. Normal *Neurospora* grows readily on a minimal medium (MM): a medium that contains several salts, sucrose, and a vitamin, but none of the other, more complex chemicals required by cells. The researchers reasoned that the mould uses the simple chemicals in the medium to synthesize all of the more complex molecules it needs for growth and reproduction. Beadle and Tatum exposed spores of *Neurospora* to X-rays. X-rays are mutagenic and cause random mutations in genes. They observed that some of the X-rayed spores did not grow unless additional nutrients, such as amino acids and vitamins, were added to the MM. Because of the mutation(s) caused by the radiation, the spores were unable to synthesize all of the complex molecules they needed to grow. Only when additional nutrients were added did the spores mature into mould.

Beadle and Tatum hypothesized that each mutated strain had a defect in a gene that coded for one of the enzymes needed to synthesize a particular nutrient that was not in the MM. The original strain could make the nutrient for itself from raw materials in the MM, but the mutated strain could not. It could grow only if the researchers added the nutrient to the MM. For example, the mutated strain that required the addition of the amino acid arginine had a defect in a gene that coded for an enzyme required in the synthesis of arginine. The assembly of arginine from raw materials is a multistep process, with different enzymes responsible for each step. Therefore, different "*arg*" mutants might differ in the particular enzyme that is defective and therefore in which step of the synthesis of arginine is blocked.

Beadle and Tatum deduced that the biosynthesis of arginine required a number of steps, and each step was controlled by a gene that coded for the enzyme for this step (**Figure 1**). Beadle and Tatum had shown the direct relationship between genes and enzymes, which they put forward as the **one gene–one enzyme hypothesis**. Their work was a keystone in the development of molecular biology. As a result of their work, they were awarded a Nobel Prize in 1958. Later, scientists recognized that the one gene–one enzyme hypothesis needed to be expanded to include other assemblies of amino acids. Many proteins are not enzymes, and many proteins consist of more than one subunit. Since this subunit is called a polypeptide, Beadle and Tatum's hypothesis was restated as the **one gene–one polypeptide hypothesis**.

one gene–one enzyme hypothesis the hypothesis, proposed by Beadle and Tatum, that each gene is unique and codes for the synthesis of a single enzyme

one gene–one polypeptide hypothesis the hypothesis that each gene is unique and codes for the synthesis of a single polypeptide; the restated version of the one gene–one enzyme hypothesis

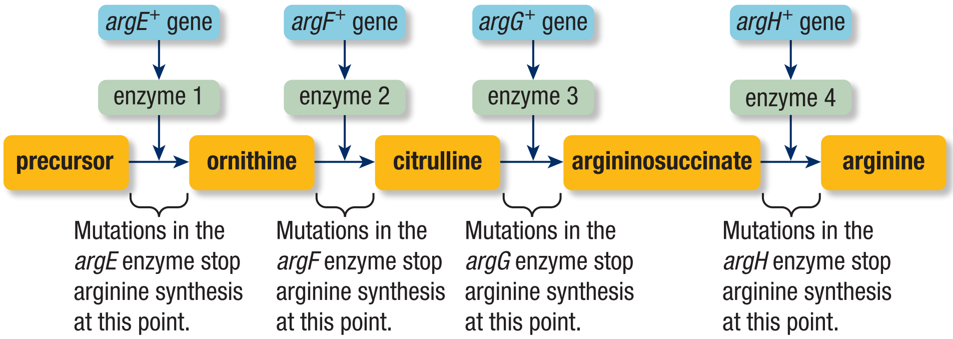

$argE^+$ gene
$argF^+$ gene
$argG^+$ gene
$argH^+$ gene
enzyme 1
enzyme 2
enzyme 3
enzyme 4
precursor
ornithine
citrulline
argininosuccinate
arginine
Mutations in the *argE* enzyme stop arginine synthesis at this point.
Mutations in the *argF* enzyme stop arginine synthesis at this point.
Mutations in the *argG* enzyme stop arginine synthesis at this point.
Mutations in the *argH* enzyme stop arginine synthesis at this point.

Figure 1 Arginine is synthesized in a biochemical pathway. Each step of the pathway is catalyzed by an enzyme, and each enzyme is coded by a different gene.

Connection between DNA, RNA, and Protein

In 1956, Francis Crick gave the name **central dogma** to the flow of information from DNA to RNA to protein (**Figure 2**). The process has two major steps: transcription and translation.

central dogma the fundamental principle of molecular genetics, which states that genetic information flows from DNA to RNA to proteins

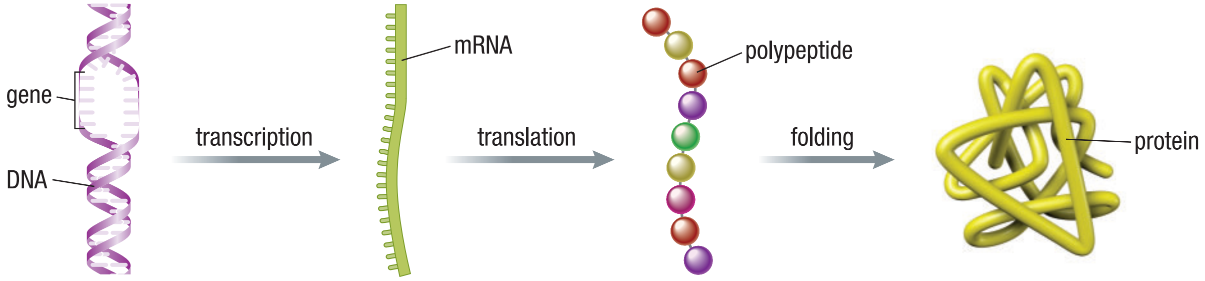


Figure 2 The central dogma of molecular genetics states that genetic information flows from DNA to RNA to protein.

Transcription is the mechanism by which the information encoded in DNA is transcribed into a complementary RNA copy. In other words, the information in one type of nucleic acid, DNA, is copied onto another type of nucleic acid, RNA. Transcription occurs in the nucleus of a eukaryotic cell. Unlike DNA, RNA is able to exit the nucleus and enter the cytosol.

transcription mechanism by which the information coded in nucleic acids of DNA is copied into the nucleic acids of RNA; something rewritten in the same language

Translation is the assembly of amino acids into a polypeptide using the information encoded in the RNA. It takes place on the ribosomes in the cytosol. The term "translation" (changing from one language to another) helps us visualize the flow of genetic information. RNA contains the information for a polypeptide in the language of bases, but this information must be translated into the language of amino acids. Transcription and translation will be discussed in more detail in Sections 7.2 and 7.3, respectively.

translation mechanism by which the information coded in the nucleic acids of RNA is copied into the amino acids of proteins

RNA: Ribonucleic Acid

Like DNA, ribonucleic acid (RNA) is a carrier of genetic information. However, RNA differs from DNA in many ways (**Table 1** and **Figure 3**). First, ribonucleic acid contains a ribose sugar rather than a deoxyribose sugar. A ribose sugar has a hydroxyl group on its 2′ carbon. Second, instead of thymine, RNA contains the base uracil. Uracil is similar in structure to thymine, except thymine has a methyl group on its 1′ carbon. Uracil in the RNA pairs with adenine in the DNA strand. Third, DNA is double stranded, whereas RNA is single stranded. When a gene is transcribed into RNA, only a single-stranded complementary copy is made. In the complementary copy, uracil is substituted for thymine.

Table 1 Comparison of DNA and RNA

Deoxyribonucleic acid	Ribonucleic acid
• double stranded	• single stranded
• adenine pairs with thymine	• adenine pairs with uracil
• guanine pairs with cytosine	• guanine pairs with cytosine
• deoxyribose sugar	• ribose sugar

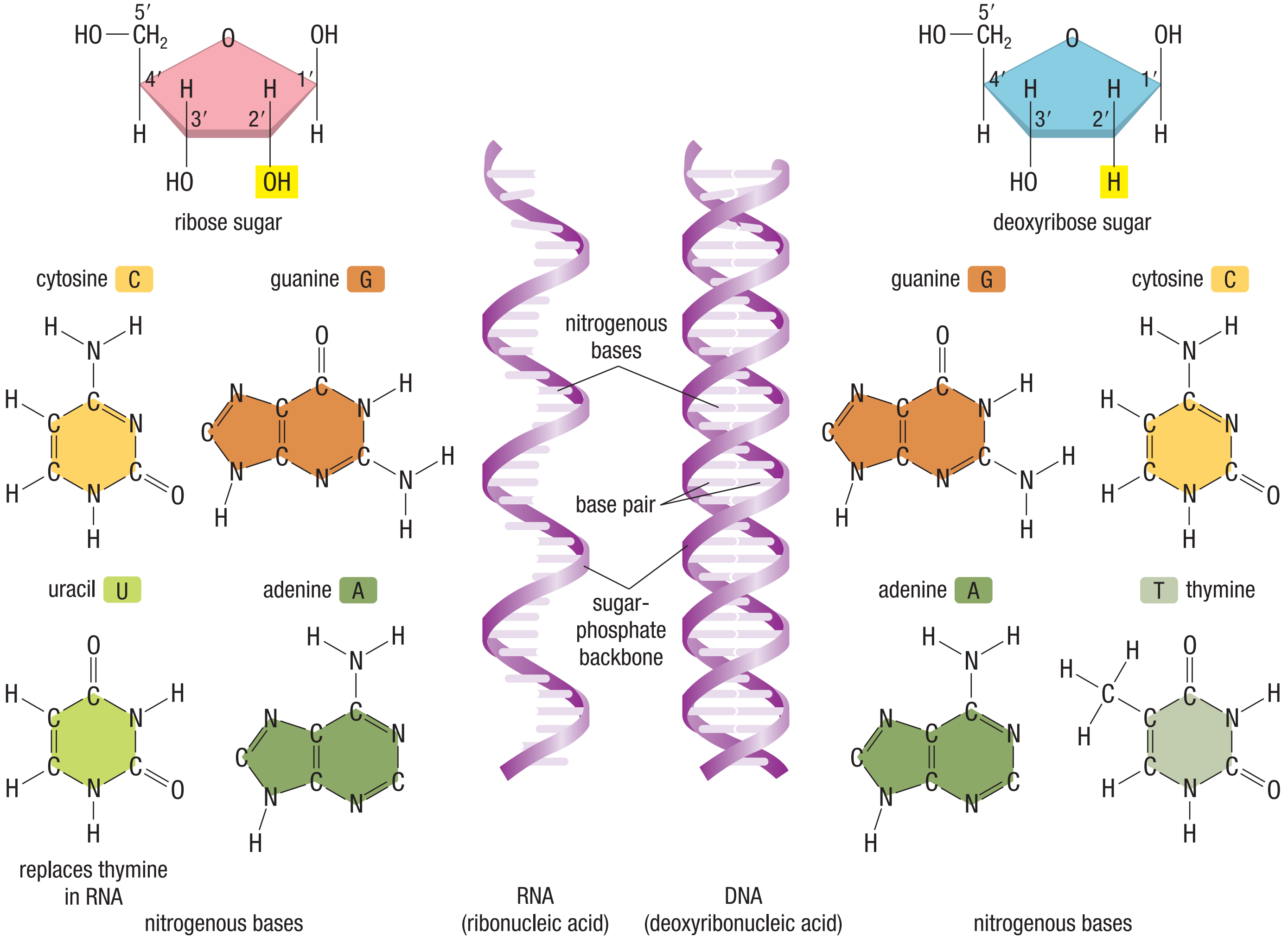


Figure 3 DNA and RNA are similar, with a few important differences: RNA is single stranded, not double stranded; RNA has uracil in place of thymine in DNA; and RNA contains a hydroxyl group (OH) at the 2′ position of the sugar, whereas DNA has a hydrogen (H) at that position (thus "deoxy" to denote the absence of oxygen).

Three major types of RNA molecules are involved in protein synthesis: messenger RNA (mRNA), transfer RNA (tRNA), and ribosomal RNA (rRNA) (**Table 2**). **Messenger RNA (mRNA)** acts as the intermediary between DNA and the ribosomes. mRNA is the RNA version of the gene encoded by DNA. It varies in length, depending on the gene that has been transcribed; the longer the gene, the longer the mRNA is.

messenger RNA (mRNA) the end product of the transcription of a gene; mRNA is translated by ribosomes into a protein

Table 2 Different Types of RNA

Types of RNA	Characteristics and key functions
messenger RNA (mRNA)	• varies in length, depending on the gene that has been copied • acts as the intermediary between DNA and the ribosomes • is translated into protein by ribosomes • is the RNA version of the gene encoded by DNA
transfer RNA (tRNA)	• functions as the delivery system of amino acids to ribosomes as they synthesize proteins • is very short, only 70 to 90 base pairs long
ribosomal RNA (rRNA)	• binds with proteins to form the ribosomes • varies in length

The role of **transfer RNA (tRNA)** is to transfer the appropriate amino acid to the ribosome to build a protein, as dictated by the mRNA template. tRNA is comparatively short in length, averaging 70 to 90 ribonucleotides (**Figure 4**). The single-stranded RNA molecule loops in on itself, forming antiparallel double strands, which are complementary to each other. **Ribosomal RNA (rRNA)** is a structural component of a ribosome and varies in length. Along with proteins, it forms the ribosome, which is the construction site for the assembly of polypeptides.

transfer RNA (tRNA) a carrier molecule that binds to a specific amino acid and adds the amino acid to the growing polypeptide chain

ribosomal RNA (rRNA) an RNA molecule within the ribosome that bonds the correct amino acid to the polypeptide chain

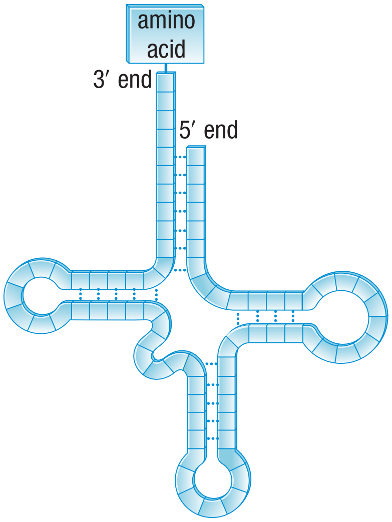


Figure 4 tRNA is composed of a single strand of RNA that loops in on itself to form antiparallel double-stranded areas.

Transcription and Translation: An Overview

The first step of protein synthesis is transcription. In transcription, the enzyme **RNA polymerase** creates an RNA molecule with a base sequence that is complementary to one strand of the DNA sequence of a given gene (**Figure 5**, next page). Transcription follows the same basic rules of complementary base pairing and nucleic acid chemistry, which you first encountered in DNA replication. For example, because the DNA template strand is read in the 3′ to 5′ direction, the mRNA will be formed in the complementary 5′ to 3′ direction. For each of the several thousand genes that can be expressed in a given cell, one DNA strand is the **template strand** and

RNA polymerase an enzyme that reads a DNA strand and creates a complementary strand of RNA

template strand the DNA strand that is copied into an mRNA molecule during gene transcription is read by the RNA polymerase. The template strand is a DNA strand that is transcribed into a precursor mRNA molecule. This **precursor mRNA** (or **pre-mRNA**), which cannot be used to produce a protein, is then modified to become an mRNA strand (to be discussed in Section 7.2). The mRNA can now exit the nucleus and enter the cytosol, where ribosomes are found.

precursor mRNA (pre-mRNA) the initial RNA transcription product

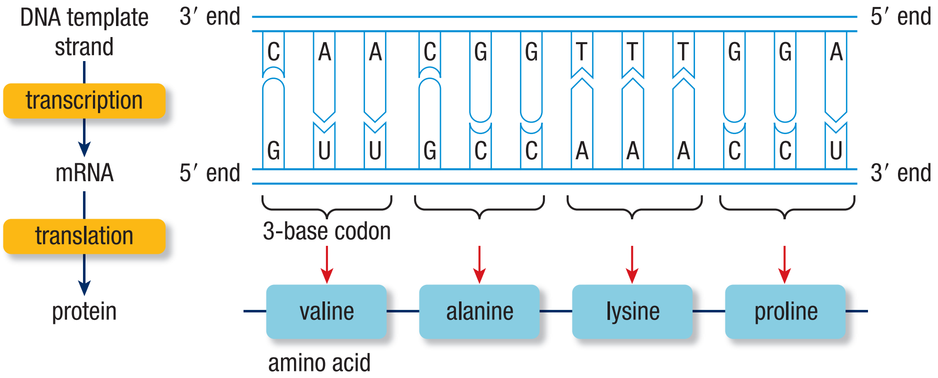


Figure 5 The relationship between a gene, the codons in an mRNA, and the amino acid sequence of a polypeptide

Translation is the second step of protein synthesis. In translation, the mRNA molecule associates with a ribosome (**Figure 6**). As the ribosome moves along the mRNA, the amino acids coded for by the mRNA are delivered by tRNA to the ribosome. The amino acids are joined together, one by one, to form the polypeptide encoded by the gene.

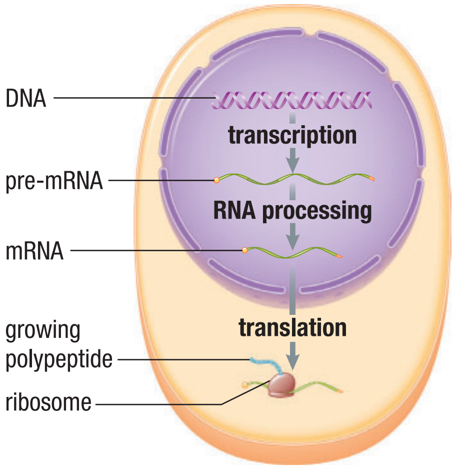


Figure 6 During transcription, RNA polymerase synthesizes a precursor-mRNA molecule (pre-mRNA, discussed in Section 7.2), which contains extra segments that are later removed. The final mRNA exits the nucleus through a nuclear pore and is translated by ribosomes in the cytosol, resulting in the synthesis of a polypeptide.

The Genetic Code: Three-Letter Words with a Four-Letter Alphabet

The specific amino acid coded for by particular DNA (or complementary RNA) bases is determined by the **genetic code**. The DNA "alphabet" consists of the four letters A, T, G, and C, and the RNA "alphabet" consists of the four letters A, U, G, and C. However, while there are only four RNA bases, there are 20 amino acids. How is nucleotide information in an mRNA molecule translated into the amino acid sequence of a polypeptide? Scientists realized that the four bases in an mRNA must be used in combinations of at least three to provide the capacity to code for 20 amino acids. If the code used only single letters (bases), only 4 different amino acids could be specified (A, T, C, and G, or 4^1). If the code used 2-letter combinations, only 16 different amino acids could be specified (AA, AT, AC, AG, TA, TT, . . . , or 4^2).

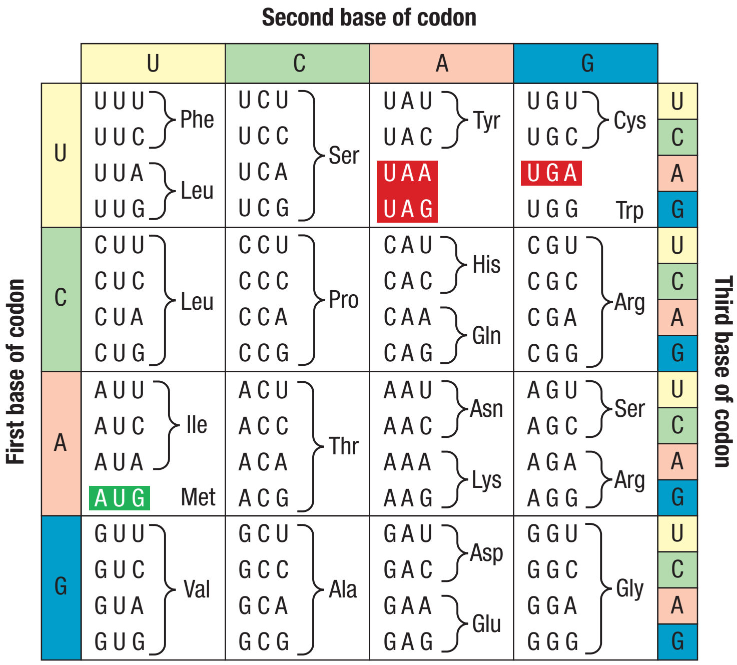
genetic code the specific coding relationship between bases and the amino acids they specify; the genetic code can be expressed in terms of either DNA or RNA bases

But if the code used 3-letter combinations, 64 different amino acids could be specified (AAA, AAT, AAC, . . . , or 4^3)—more than enough to code for 20 amino acids.

Scientists now know that the genetic code is indeed a 3-letter code. Each 3-letter combination is called a **codon**. The codons are in the 5′ to 3′ order in the mRNA. Figure 5 (page 316) illustrates the relationship between a gene, codons on an mRNA, and the amino acid sequence of a polypeptide. Of the 64 codons, 61 specify amino acids (**Figure 7** and **Table 3**). These are known as "sense codons." For example, one of these codons, AUG, specifies the amino acid methionine. It is usually the first codon translated in any mRNA in both prokaryotes and eukaryotes. Therefore, AUG is called a **start codon**, or **initiator codon**.

codon a group of three base pairs that code for an individual amino acid

start codon (initiator codon) the codon that signals the start of a polypeptide chain and initiates translation


Second base of codon

First base of codon	U	C	A	G	Third base of codon
U	UUU Phe	UCU Ser	UAU Tyr	UGU Cys	U
	UUC	UCC	UAC	UGC	C
	UUA Leu	UCA	UAA	UGA	A
	UUG	UCG	UAG	UGG Trp	G
C	CUU Leu	CCU Pro	CAU His	CGU Arg	U
	CUC	CCC	CAC	CGC	C
	CUA	CCA	CAA Gln	CGA	A
	CUG	CCG	CAG	CGG	G
A	AUU Ile	ACU Thr	AAU Asn	AGU Ser	U
	AUC	ACC	AAC	AGC	C
	AUA	ACA	AAA Lys	AGA Arg	A
	AUG Met	ACG	AAG	AGG	G
G	GUU Val	GCU Ala	GAU Asp	GGU Gly	U
	GUC	GCC	GAC	GGC	C
	GUA	GCA	GAA Glu	GGA	A
	GUG	GCG	GAG	GGG	G

Figure 7 The genetic code, written in the form in which the codons appear in mRNA: The AUG initiator codon, which codes for methionine, is shown in green; the three terminator codons are shown in red. The triplet sequences are in the 5′ to 3′ order.

Table 3 Amino Acids and Their Abbreviations

Amino acid	Three-letter abbreviation	Amino acid	Three-letter abbreviation
alanine	Ala	leucine	Leu
arginine	Arg	lysine	Lys
asparagine	Asn	methionine	Met
aspartic acid	Asp	phenylalanine	Phe
cysteine	Cys	proline	Pro
glutamic acid	Glu	serine	Ser
glutamine	Gln	threonine	Thr
glycine	Gly	tryptophan	Trp
histidine	His	tyrosine	Tyr
isoleucine	Ile	valine	Val

The three codons that do not specify amino acids—UAA, UAG, and UGA—are called **stop codons** (also called "nonsense codons" or "termination codons"). They act as "periods," indicating the end of a polypeptide-encoding sentence. When a ribosome reaches one of the stop codons, polypeptide synthesis stops and the newly synthesized polypeptide chain is released from the ribosome.

stop codon a codon that signals the end of a polypeptide chain and causes the ribosome to terminate translation

Only two amino acids, methionine and tryptophan, are specified by a single codon. All the rest are represented by at least two, and some by as many as six, codons. In other words, there are many synonyms in the genetic code. For example, UGU and UGC both specify cysteine, whereas CCU, CCC, CCA, and CCG all specify proline. This feature is known as redundancy and is called the wobble hypothesis. The presence of this redundancy allows the third base in a codon to change (wobble), while still allowing the codon to code for the same amino acid. Notice how both cysteine codons follow the pattern UG_ and all proline codons follow the pattern CC_. The wobble hypothesis is discussed in more detail in Section 7.3.

The genetic code is universal. With a few exceptions, the same codons specify the same amino acids in all living organisms, and also in all viruses. The universality of the genetic code indicates that it was established, in its present form, very early in the evolution of life and has remained virtually unchanged through billions of years of evolutionary history. Minor exceptions to the universality of the genetic code have been found in a few organisms, including yeast, some protozoans, and a prokaryote, and in the DNA of mitochondria and chloroplasts.

7.1 Review

Summary

- Beadle and Tatum's experiments exposing bread mould to X-ray radiation resulted in their one gene–one enzyme hypothesis, later expanded to the one gene–one polypeptide hypothesis.
- A gene is a DNA sequence of bases that specifies the exact sequence of assembly of amino acids, by a ribosome, into a unique polypeptide.
- The central dogma outlines the flow of information from DNA to mRNA to protein.
- DNA differs from RNA. RNA is a single strand, it contains a ribose sugar instead of a deoxyribose sugar, and it contains uracil instead of thymine.
- Three types of RNA are involved in protein synthesis: messenger RNA (mRNA), transfer RNA (tRNA), and ribosomal RNA (rRNA).
- In transcription, the information encoded in DNA is passed to a complementary mRNA molecule. The code is rewritten using the same nucleotides that are found in DNA, except for uracil, which replaces the thymine in DNA.
- In translation, the sequence of nucleotides in an mRNA molecule specifies an amino acid sequence in a polypeptide. A ribosome uses the mRNA sequence to assemble a polypeptide, with the help of tRNA.
- The genetic information that specifies a single amino acid is a sequence of three bases, called a codon. A single codon (AUG) signals the start of translation, and three codons (UAA, UAG, and UGA) signal the termination.

Questions

1. Describe Beadle and Tatum's experiment. How did their results support their one gene–one enzyme hypothesis? K/U
2. Beadle and Tatum observed that different mutant strains of *Neurospora* required the addition of different nutrients to the minimal medium (MM) in order to grow. Explain this observation. K/U
3. Using a Venn diagram, compare the structure of DNA and RNA. K/U C
4. What are the three major classes of RNA, and what is the function of each? K/U
5. Compare and contrast transcription and translation in terms of their purpose and location. K/U
6. The sequence of a fragment of one strand of DNA is AATTGCATATACGGGAAATACGACCGG. Transcribe this sequence into mRNA. K/U T/I
7. A genetic code that is based on triplet codons can generate 64 unique combinations. How many combinations of codons could be generated using a four-base codon? How many could be generated using a five-base codon? T/I
8. The following mRNA strand is being used to assemble a polypeptide strand by a ribosome:

   5′-AUGCUUGCUCAUCGGGGUUUUAA-3′

   (a) Write out the amino acids that will be assembled, in their correct order.

   (b) Provide an alternative mRNA sequence with four or more changes that would translate to the same amino acid sequence. T/I
9. Write out all possible RNA base codons that could code for the following amino acid sequences. T/I

   (a) Arg-Trp

   (b) Leu-Pro

   (c) Met-Phe-Trp
10. Differentiate between a stop codon and a start codon. K/U
11. What is the wobble hypothesis? K/U
12. Suppose that you are studying a protein with the primary sequence Met-Leu-His-Asn-Ala. Write out one double-stranded DNA sequence for this peptide. (Yes, there are MANY possible answers!) Include the start codon and a stop codon. Indicate the 3′ and 5′ ends of the DNA. Which is the template strand? T/I

Transcription: DNA-Directed RNA Synthesis

7.2

During transcription, the DNA code is chemically rewritten as an RNA code. This occurs within the nucleus. Transcription is divided into three sequential processes: initiation, elongation, and termination. Refer to **Figure 1** (next page) as you read the next three sections describing these three processes of transcription.

Initiation

In both prokaryotes and eukaryotes, the process of transcription begins when the enzyme RNA polymerase binds to the DNA and unwinds it near the beginning of a gene (Figure 1, Step 1). The binding occurs at a **promoter**: a specialized sequence on one strand of DNA, located just upstream from the start of the gene. A key element of the promoter in eukaryotes is the **TATA box**: a section of DNA with a high percentage of thymine and adenine bases, which is recognized by RNA polymerase. Prokaryotes have a TATAAT sequence instead of a TATA box for this purpose. Adenine and thymine share only two hydrogen bonds, whereas guanine and cytosine share three hydrogen bonds. Since less energy is needed to break two bonds, the RNA polymerase expends less energy opening up the DNA helix if it possesses a high concentration of adenine and thymine base pairs. The part of the gene that is to be transcribed into RNA is called the transcription unit.

promoter a nucleotide sequence that lies just before a gene and allows for the binding of RNA polymerase

TATA box a region of the promoter that enables the binding of RNA polymerase

Elongation

Once the RNA polymerase binds to the promoter and opens the DNA double helix, it starts to build the single-stranded RNA molecule. RNA polymerase, unlike DNA polymerase, can begin making the complementary copy without needing a primer to be already in place. RNA is made in the $5'{\rightarrow}3'$ direction, using the $3'{\rightarrow}5'$ DNA strand as a template strand. The opposite strand of DNA—the strand that is not being copied—is known as the **coding strand**, since it contains the same base-pair sequence as the new RNA molecule, except for the absence of uracil and the presence of thymine. Remember that the template strand contains the sequence that is complementary to the sequence that is going to be transcribed. Therefore, the beginning of the RNA strand is the 5′ end, and the other end is the 3′ end.

coding strand the DNA strand that is not being copied but contains the same sequence as the new RNA molecule

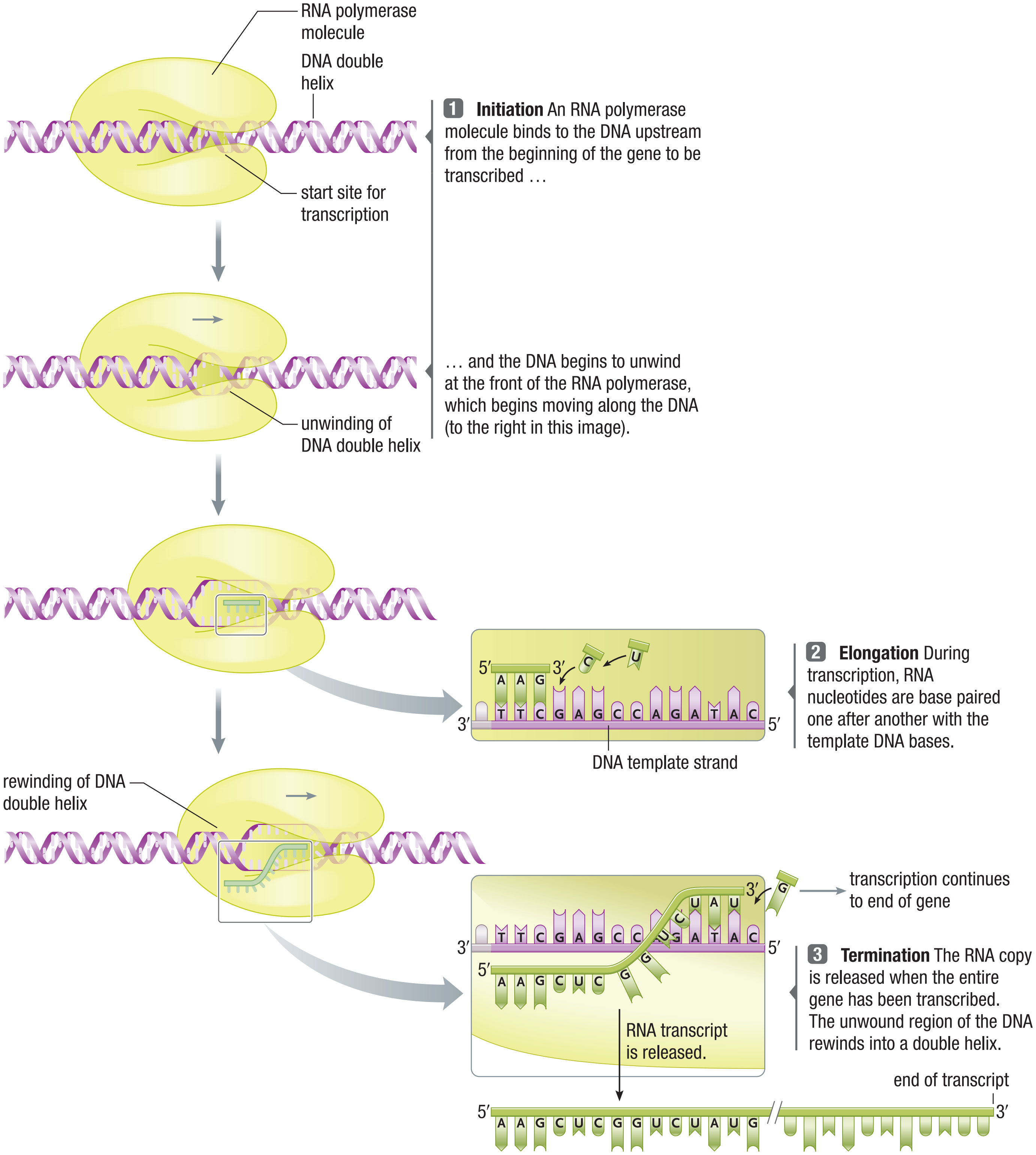
As RNA polymerase moves along the DNA, it unwinds the DNA at the forward end of the enzyme. The new RNA molecule elongates as nucleotides are added, one by one (Figure 1, Step 2). The new RNA molecule winds temporarily with the template strand of the DNA into a hybrid RNA–DNA double helix. Beyond this short region of pairing, the growing RNA strand unwinds from the DNA and extends from the RNA polymerase as a single nucleotide chain. As the RNA polymerase passes, the DNA double helix reforms.

Once an RNA polymerase molecule has started transcription and progressed past the beginning of a gene, another molecule of RNA polymerase may start producing another RNA molecule if there is room at the promoter. Most genes undergoing transcription have many RNA polymerase molecules spaced closely along them, and each molecule makes an RNA transcript. When cells require a particular protein, they usually need to produce thousands or even millions of copies. For example, a single red blood cell contains 375 million hemoglobin molecules. The process of making hemoglobin would be very slow if the gene had only one RNA polymerase enzyme making one mRNA molecule at a time. Many copies of mRNA are made so that many ribosomes can mass-produce the protein required.

Termination

termination sequence a sequence of bases at the end of a gene that signals the RNA polymerase to stop transcribing

The transcription of a protein-coding gene is terminated when RNA polymerase recognizes a **termination sequence** (Figure 1, Step 3). In prokaryotes, one termination mechanism involves a protein binding to the mRNA and stopping transcription.


RNA polymerase molecule
DNA double helix
start site for transcription
unwinding of DNA double helix
5′
3′
A A G
C
U
T T C G A G C C A G A T A C
3′
5′
DNA template strand
rewinding of DNA double helix
3′
U A U
G
C
U
T T C G A G C C A G A T A C
3′
5′
5′
A A G C U C
G
G
transcription continues to end of gene
RNA transcript is released.
end of transcript
5′
A A G C U C G G U C U A U G
3′

1 Initiation An RNA polymerase molecule binds to the DNA upstream from the beginning of the gene to be transcribed …

… and the DNA begins to unwind at the front of the RNA polymerase, which begins moving along the DNA (to the right in this image).

2 Elongation During transcription, RNA nucleotides are base paired one after another with the template DNA bases.

3 Termination The RNA copy is released when the entire gene has been transcribed. The unwound region of the DNA rewinds into a double helix.

Figure 1 Transcribing a gene into precursor mRNA in eukaryotes. There are three stages: initiation, elongation, and termination. RNA polymerase moves along the gene, separating the two DNA strands to allow RNA synthesis in the 5′ → 3′ direction. The 3′ → 5′ DNA strand is used as a template.

Another termination mechanism involves the mRNA binding with itself in a hairpin loop and stopping transcription. In eukaryotes, one termination sequence is a string of adenines, which are transcribed as a string of uracils on the RNA. Nuclear proteins bind to the polyuracil site and stop transcription. The newly synthesized RNA then dissociates from the DNA template strand. Transcription ceases, and the RNA polymerase is free to bind to another promoter region and transcribe another gene.

Post-transcriptional Modifications

At this point, the newly transcribed eukaryotic RNA, known as the primary transcript or precursor mRNA (or pre-mRNA), is vulnerable to the enzymes and conditions outside the cell nucleus. The pre-mRNA must undergo additional modifications before it can exit the nucleus and reach the ribosome.

One modification is the addition of a chain of 50 to 250 adenine nucleotides, one nucleotide at a time, to the 3′ end by an enzyme called poly-A polymerase (**Figure 2**). The chain of adenine nucleotides, called the **poly(A) tail**, enables mRNA to be translated efficiently and protects it from attack by RNA-digesting enzymes in the cytosol.

poly(A) tail a chain of adenine nucleotides that are added to the 3′ end of the pre-mRNA molecule to protect it from enzymes in the cytosol

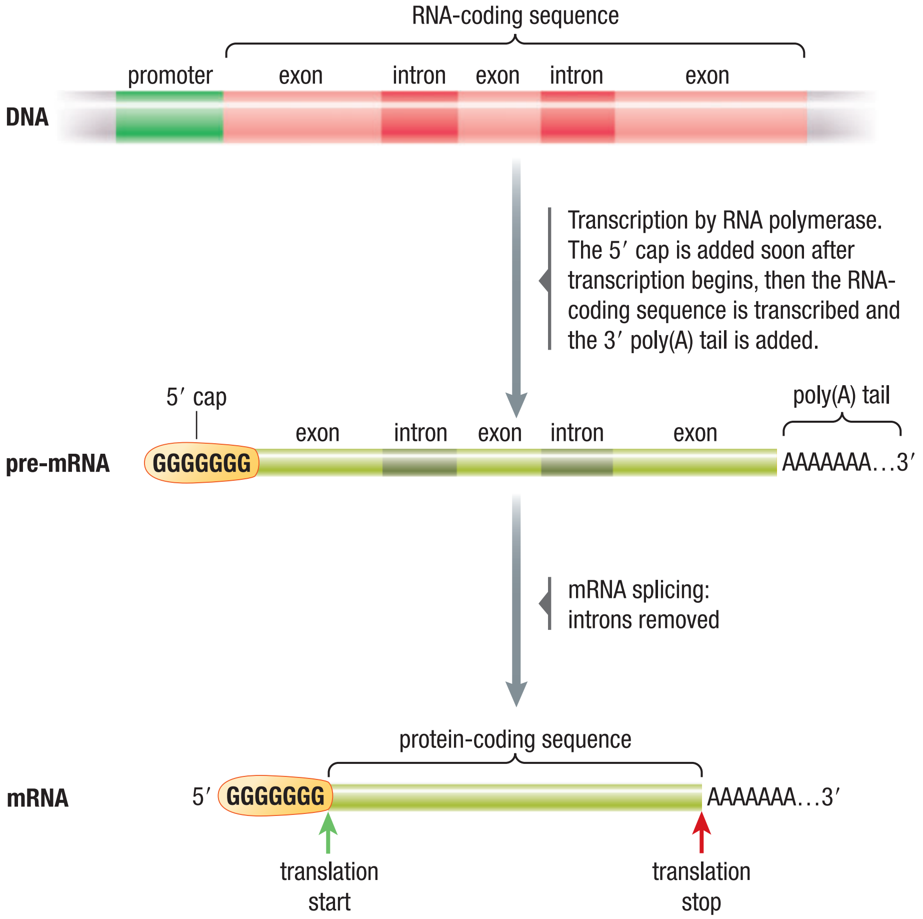


Figure 2 The relationship between a eukaryotic protein-coding gene, the pre-mRNA transcribed from it, and the mRNA processed from the pre-mRNA

Modifications are also made at the beginning of the pre-mRNA transcript, where a **5′ cap**, consisting of seven Gs, is added by a different enzyme complex. The 5′ cap functions as the initial attachment site for mRNAs to ribosomes, to allow for translation. This whole process is known as capping and tailing.

5′ cap a sequence of seven Gs that is added to the start of a pre-mRNA molecule; ribosomes recognize this site and use it as the site of initial attachment

exon a sequence of DNA or RNA that codes for part of a gene

intron a non-coding sequence of DNA or RNA

The precursor mRNA is still not ready to exit the nucleus. Further modifications need to be made. The DNA of a eukaryotic gene is composed of coding regions known as **exons** and non-coding regions known as **introns**. The introns are interspersed among the exons and are transcribed into pre-mRNAs (Figure 2). However, the introns do not code for part of the protein. If they were left in the mRNA, they would alter the sequence of the amino acids that are used to build the protein. This would result in additional amino acids and a protein that would not fold as it should and therefore would not function correctly. Therefore, the introns are deleted and the exons are retained in fully processed mRNA. The majority of known eukaryotic genes contain at least one intron, and some contain more than 60. Prokaryrote DNA does not contain any introns.

spliceosome an enzyme-protein complex that removes introns from the mRNA

small ribonucleoprotein (snRNP) a protein that binds to introns and signals them for removal

In the nucleus, a process called mRNA splicing removes the introns from pre-mRNAs and joins the exons together. mRNA splicing occurs in a **spliceosome**: a complex formed between the pre-mRNA and a handful of **small ribonucleoproteins** called **snRNPs** (pronounced snurps). The snRNPs bind in a particular order to an intron in the pre-mRNA (**Figure 3**). The first snRNPs are those that recognize and form complementary base pairs with mRNA sequences at the junctions of the intron and adjacent exons. Other snRNPs are then recruited, causing the intron to loop out and bring the two exon ends close together. At this point, an active spliceosome has been formed, releasing the intron and joining together the two exons. The cutting and splicing are so exact that not a single base of an intron is retained in the finished mRNA, and not a single base is removed from the exons.

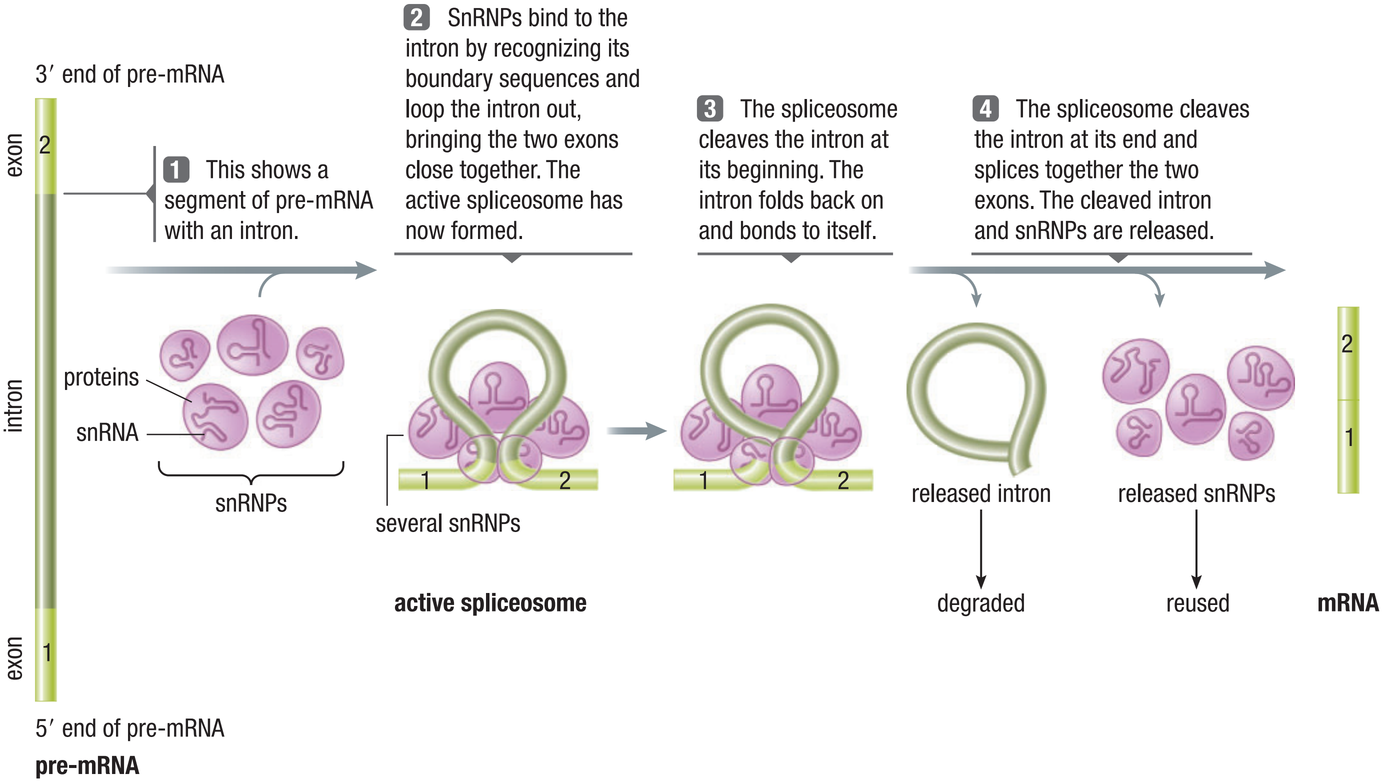

3′ end of pre-mRNA
exon
2
intron
exon
1
5′ end of pre-mRNA
pre-mRNA
1 This shows a segment of pre-mRNA with an intron.
proteins
snRNA
snRNPs
2 SnRNPs bind to the intron by recognizing its boundary sequences and loop the intron out, bringing the two exons close together. The active spliceosome has now formed.
1
2
several snRNPs
active spliceosome
3 The spliceosome cleaves the intron at its beginning. The intron folds back on and bonds to itself.
1
2
4 The spliceosome cleaves the intron at its end and splices together the two exons. The cleaved intron and snRNPs are released.
released intron
degraded
released snRNPs
reused
2
1
mRNA

Figure 3 Introns are removed from eukaryotic precursor mRNA, and exons are joined together.

alternative splicing a process that produces different mRNAs from pre-mRNA (exons and introns), allowing more than one possible polypeptide to be made from a single gene

Exons may be joined in different combinations to produce different mRNAs from a single DNA gene sequence. A mechanism called **alternative splicing** greatly increases the number and variety of proteins encoded by a single gene. According to current estimates, three-quarters of all human pre-mRNAs are subjected to alternative splicing. In each case, the different mRNAs that are produced from the parent pre-mRNA are translated to produce a family of related proteins with various combinations of amino acid sequences derived from the exons. Each protein in the family, then, varies in its function. Alternative splicing helps us understand why humans with only about 20 000 genes can produce approximately 100 000 proteins. After the final mRNA has been produced, it is ready to leave the nucleus and be translated by a ribosome.

Transcription in Eukaryotes versus Prokaryotes

Transcription is similar in eukaryotes and prokaryotes, but not identical. For example, a single type of RNA polymerase is used in prokaryotes to transcribe all the genes, both those that encode proteins and those that code for non-protein molecules such as tRNA and rRNA. In contrast, eukaryotic cells use different types of RNA polymerase enzymes depending on what is being transcribed. RNA polymerase type II transcribes protein-coding genes, while RNA polymerase types I and III transcribe the non-protein–coding genes (that produce rRNA and tRNA). The key differences in transcription between eukaryotes and prokaryotes are summarized in **Table 1**.

Table 1 Comparison of Transcription in Eukaryotes and Prokaryotes

Variable	Prokaryotes	Eukaryotes
location	Transcription occurs throughout the cell.	Transcription takes place in the nucleus.
enzymes	A single type of RNA polymerase transcribes all types of genes.	Different RNA polymerases are used to transcribe genes that encode protein (RNA polymerase II) and genes that do not encode protein (RNA polymerase I, III).
elongation	Bases are added quickly (15 to 20 nucleotides per second).	Bases are added slowly (5 to 8 nucleotides per second).
promoters	The promoters are less complex than those in eukaryotes.	The promoters are immediately upstream of protein-coding genes, and they are more complex than those in prokaryotes.
termination	A protein binds to the mRNA and cleaves it, or the mRNA binds with itself.	Nuclear proteins bind to the polyuracil site and terminate transcription.
introns and exons	There are no introns.	There are both introns and exons.
product	Transcription results in mRNA ready to be translated into protein by ribosomes.	Transcription results in pre-mRNA, which must be modified to protect the final mRNA from degradation in the cytosol and to remove introns.

7.2 Review

Summary

- Transcription has three stages: initiation, elongation, and termination. One strand of the double-stranded DNA is used as a template for the synthesis of a complementary single-stranded RNA molecule.
- Initiation begins when RNA polymerase binds to a promoter region, which is upstream of the gene to be transcribed, and begins to unwind the DNA molecule.
- During elongation, a complementary RNA strand is synthesized in the 5′ to 3′ direction. Adenine in the DNA is paired with uracil in RNA.
- When RNA polymerase reaches a termination sequence, elongation ceases.
- In eukaryotes, post-transcriptional modifications include a 5′ cap of seven Gs added to the 5′ end, a string of adenines added to the 3′ end, and introns excised by spliceosomes. There are no modifications to prokaryotic mRNA.
- Transcription differs in eukaryotes and prokaryotes with respect to location, speed, post-transcriptional modifications, and types of RNA polymerase enzymes.

Questions

1. List and describe the three stages of transcription. K/U
2. If the DNA template strand has the sequence 3′-CAAATTGGCTTATTACCGGATG-5′, what would be the sequence of an RNA molecule transcribed from it? T/I
3. Explain the role of each of the following in transcription. K/U
   (a) promoter
   (b) RNA polymerase
   (c) spliceosomes
4. Differentiate between introns and exons. K/U
5. What are the key differences between transcription in eukaryotes and prokaryotes? K/U
6. Compare and contrast DNA replication and transcription. How are they similar? How are they different? Present your answer in table form. T/I C
7. How is it possible for an organism to produce more proteins than it has genes for? K/U
8. As a graduate student in a university laboratory, you have been challenged with the problem of determining whether a sample of mRNA is from a eukaryotic cell or a prokaryotic cell. You have been provided with a nucleotide sequencer, which will help you determine the DNA sequence. What features in the sequence will you look for to determine whether the mRNA is eukaryotic or prokaryotic? T/I
9. Suppose that you are provided with a sample of eukaryotic DNA. You divide the sample into three separate reaction mixtures and perform an experiment. Once transcription is complete, you analyze the base composition of mRNA from each mixture. You obtain the results in **Table 2**. Based on these results, answer the questions below. T/I

Table 2 Experimental Results

	A	G	C	T	U
DNA Strand I	19.1	26.0	31.0	23.9	0
DNA Strand II	24.2	30.8	25.7	19.3	0
mRNA Strand A	19.7	25.9	30.8	0	24.0
mRNA Strand B	24.1	30.9	25.9	0	19.0

   (a) Which strand of DNA served as the template for the synthesis of mRNA strand A? Which strand served as the template for the synthesis of mRNA strand B? Explain your reasoning.
   (b) Explain why the percentage of adenine is higher in the mRNA strands than in the DNA strands.
10. How does the absence of a nucleus in prokaryotes prevent prokaryotes from controlling gene expression by modifying RNA after transcription? T/I

Translation: Nucleic Acid to Polypeptide

Transcription uses the message coded in a DNA strand as a template for the synthesis of a complementary single-stranded mRNA molecule. The next step in the process of manufacturing a protein is translating the information coded in mRNA to a protein. In translation, the encoded message is read, codon by codon, by a ribosome and, with the presence of transfer RNA molecules, the ribosome assembles one amino acid at a time into a polypeptide chain.

tRNA

The ribosome alone cannot synthesize the polypeptide chain. Transfer RNA molecules (tRNAs) are small RNAs, about 70 to 90 nucleotides long. In comparison, mRNAs are typically hundreds of nucleotides long. tRNAs have a highly distinctive structure that serves their role in translation (**Figure 1**). All tRNAs have regions that base pair with themselves, winding into four double-helical segments to form a cloverleaf pattern. At the tip of one of the double-helical segments is an **anticodon**: a 3-nucleotide segment that pairs with a codon in an mRNA. At the other end of the cloverleaf is a region that carries the amino acid that corresponds to the anticodon. For example, a tRNA that is linked to serine (Ser) pairs with the codon 5′-AGU-3′ in mRNA. The anticodon of the tRNA that pairs with this codon is 3′-UCA-5′.

Recall that 61 of the 64 codons of the genetic code specify an amino acid. However, this does not mean that we need 61 different tRNAs to read the different codons. Francis Crick's wobble hypothesis proposed that the complete set of 61 codons can be read by fewer than 61 distinct tRNAs because of the particular pairing properties of the bases in the anticodons. That is, the pairing of the anticodon with the first two nucleotides of the codon is always precise, but most anticodons have flexibility in pairing with the third nucleotide of the codon. For example, UAU and UAC both code for tyrosine. If the tRNA's anticodon is AUA, it can still bind to the codon UAC, despite its complementarity being UAU. Either way, tyrosine is added on (**Figure 2**).

anticodon the complementary sequence of base pairs on a tRNA that corresponds to a codon on an mRNA

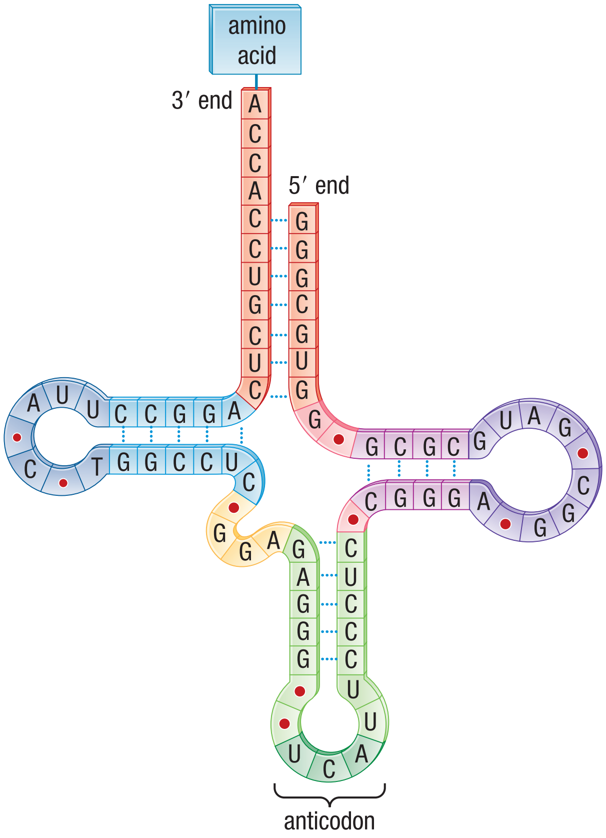


Figure 1 The structure of tRNA: The red dots show sites where bases are chemically modified into other forms.

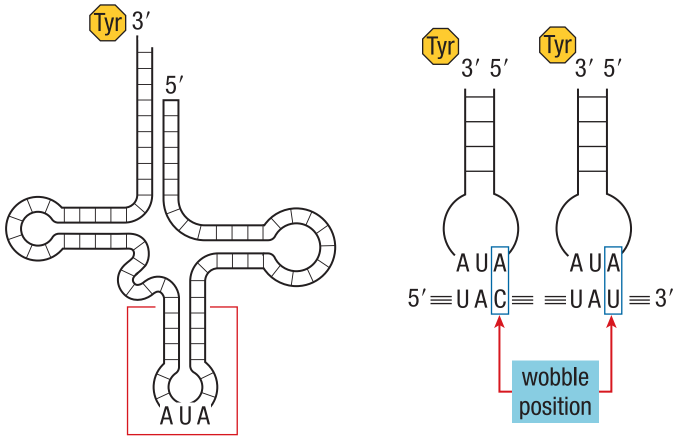


Figure 2 The wobble hypothesis: Even though the third nucleotide in the mRNA differs (UAU and UAC), the same tRNA with the anticodon AUA will deliver tyrosine to the growing polypeptide chain. Therefore, fewer types of tRNA are required to deliver the 20 amino acids, even though 61 codons exist in the genetic code.

aminoacylation the process by which a tRNA molecule is bound to its corresponding amino acid

aminoacyl–tRNA a molecule of transfer RNA bound to its associated amino acid

The process of adding an amino acid to a tRNA is called **aminoacylation** (literally, the addition of an amino acid) or "charging" the tRNA. The finished product, a tRNA linked to its correct amino acid, is called an **aminoacyl–tRNA**. Aminoacylation is catalyzed by 20 different aminoacyl–tRNA synthetase enzymes, one for each of the 20 amino acids. The energy in the aminoacyl–tRNA eventually drives the formation of the peptide bond that links the amino acids during translation.

With the tRNAs attached to their corresponding amino acids, our attention moves to the ribosome, where the amino acids are removed from tRNAs and linked together into polypeptide chains.

Ribosomes

Ribosomes carry out protein synthesis by translating mRNA into chains of amino acids. Like automated machines that use a series of steps to form complicated metal or plastic parts, ribosomes use an information tape—an mRNA molecule—to accomplish a task. For ribosomes, the task is joining amino acids in ordered sequences to make polypeptide chains.

A ribosome is made up of two different-sized parts, called the large and small ribosomal subunits (**Figure 3**). Each subunit is made up of a combination of ribosomal RNA (rRNA) and ribosomal proteins. To fulfill its role in translation, the ribosome has special binding sites that actively bring together mRNA with aminoacyl–tRNAs (Figure 3). One such site is where the mRNA threads through the ribosome. The A (aminoacyl) site is where the incoming aminoacyl–tRNA, carrying the next amino acid to be added to the polypeptide chain, binds to the mRNA. The P (peptidyl) site is where the tRNA, carrying the growing polypeptide chain, is bound. The E (exit) site is where an exiting tRNA leaves the ribosome.

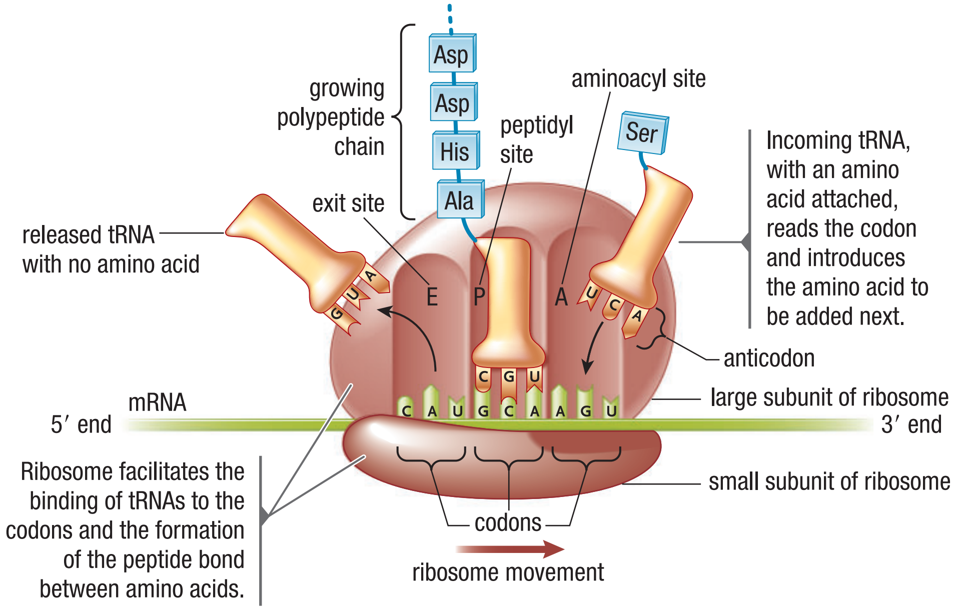

Asp
Asp
His
Ala
growing polypeptide chain
aminoacyl site
peptidyl site
Ser
exit site
Incoming tRNA, with an amino acid attached, reads the codon and introduces the amino acid to be added next.
released tRNA with no amino acid
G U A
E
P
A
U C A
anticodon
C G U
C A U G C A A G U
mRNA
5′ end
large subunit of ribosome
3′ end
small subunit of ribosome
Ribosome facilitates the binding of tRNAs to the codons and the formation of the peptide bond between amino acids.
codons
ribosome movement

Figure 3 A ribosome assembles amino acids into a polypeptide chain. A tRNA molecule, with an amino acid bound to it, enters the ribosome on the right (A site). The anticodon on the tRNA pairs with the codon in the mRNA. Its amino acid will then be added to the growing polypeptide, which is currently attached to the tRNA in the middle of the ribosome (P site).

The Process of Translation

There are three major stages of translation: initiation, elongation, and termination. The binding of the ribosome subunits to the mRNA molecule and the recognition of the start codon initiates translation. The start codon AUG corresponds to the amino acid methionine. The polypetide chain is elongated as the codons (sets of three nucleotides) are read. tRNA molecules deliver the appropriate amino acids to the ribosome, where they are added to the end of the growing chain. The termination process recognizes where to stop adding amino acids to the growing polypeptide. A stop codon terminates translation. Multiple ribosomes along the same mRNA can simultaneously translate the mRNA and make multiple copies of the protein.

Initiating Translation

The first stage in assembling a protein, using mRNA as a template, is called initiation. Translation is initiated when the large and small ribosomal subunits associate with an mRNA molecule, and the first aminoacyl–tRNA of the new protein chain becomes bound to the AUG start codon. The aminoacyl–tRNA that is used for initiation is a specialized initiator tRNA, which has an anticodon to the methionine-specifying AUG start codon.

In Step 1 of the initiation process, the initiator methionine–tRNA (met–tRNA) forms a complex with the small ribosomal subunit (**Figure 4**). The complex binds to the mRNA at the 5′ cap and then moves along the mRNA (a process called scanning) until it reaches the first AUG codon (Step 2). This is the start codon, and it is recognized by the anticodon of the Met–tRNA. The large ribosomal subunit then binds to complete the ribosome (Step 3). At the end of initiation, the initiator Met–tRNA is in the P site.

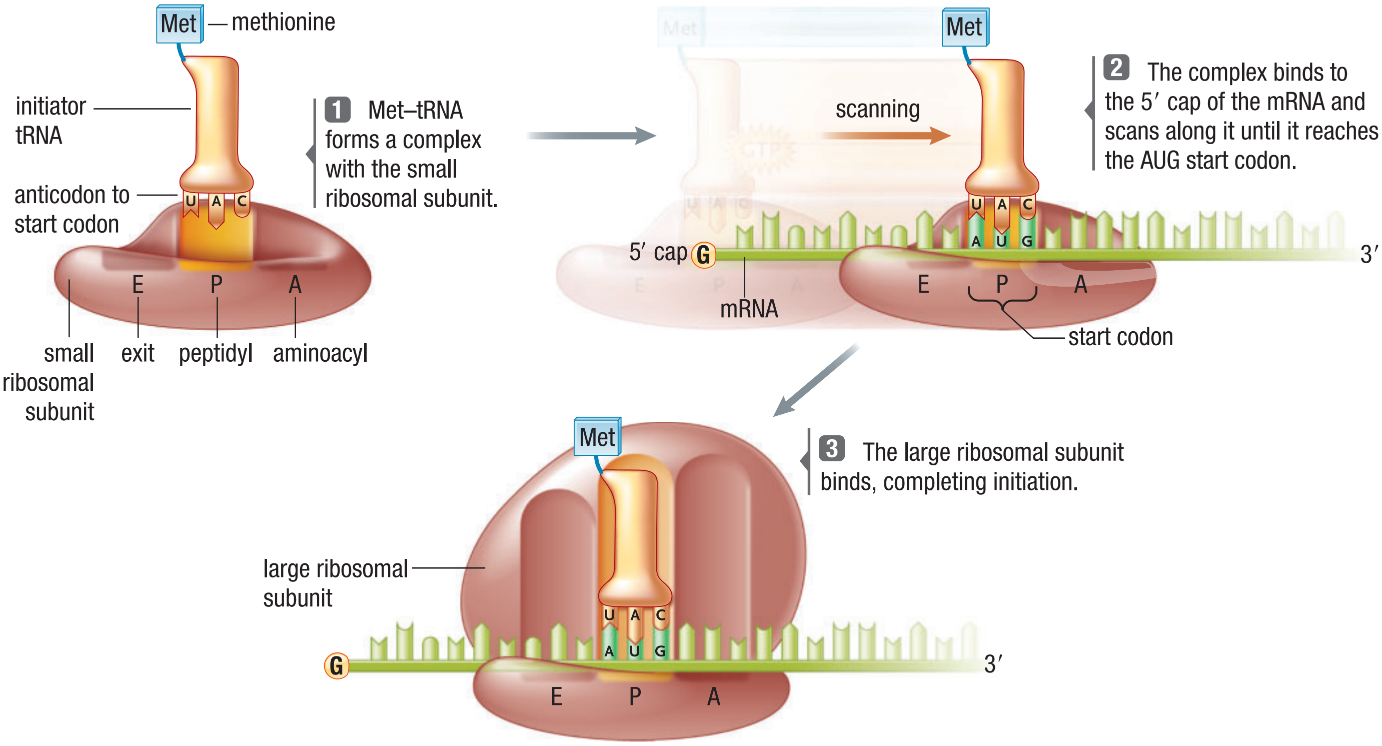

Met
methionine
initiator tRNA
anticodon to start codon
U A C
E P A
small ribosomal subunit
exit
peptidyl
aminoacyl
1 Met–tRNA forms a complex with the small ribosomal subunit.
scanning
5′ cap
G
mRNA
A U G
3′
start codon
2 The complex binds to the 5′ cap of the mRNA and scans along it until it reaches the AUG start codon.
3 The large ribosomal subunit binds, completing initiation.
large ribosomal subunit

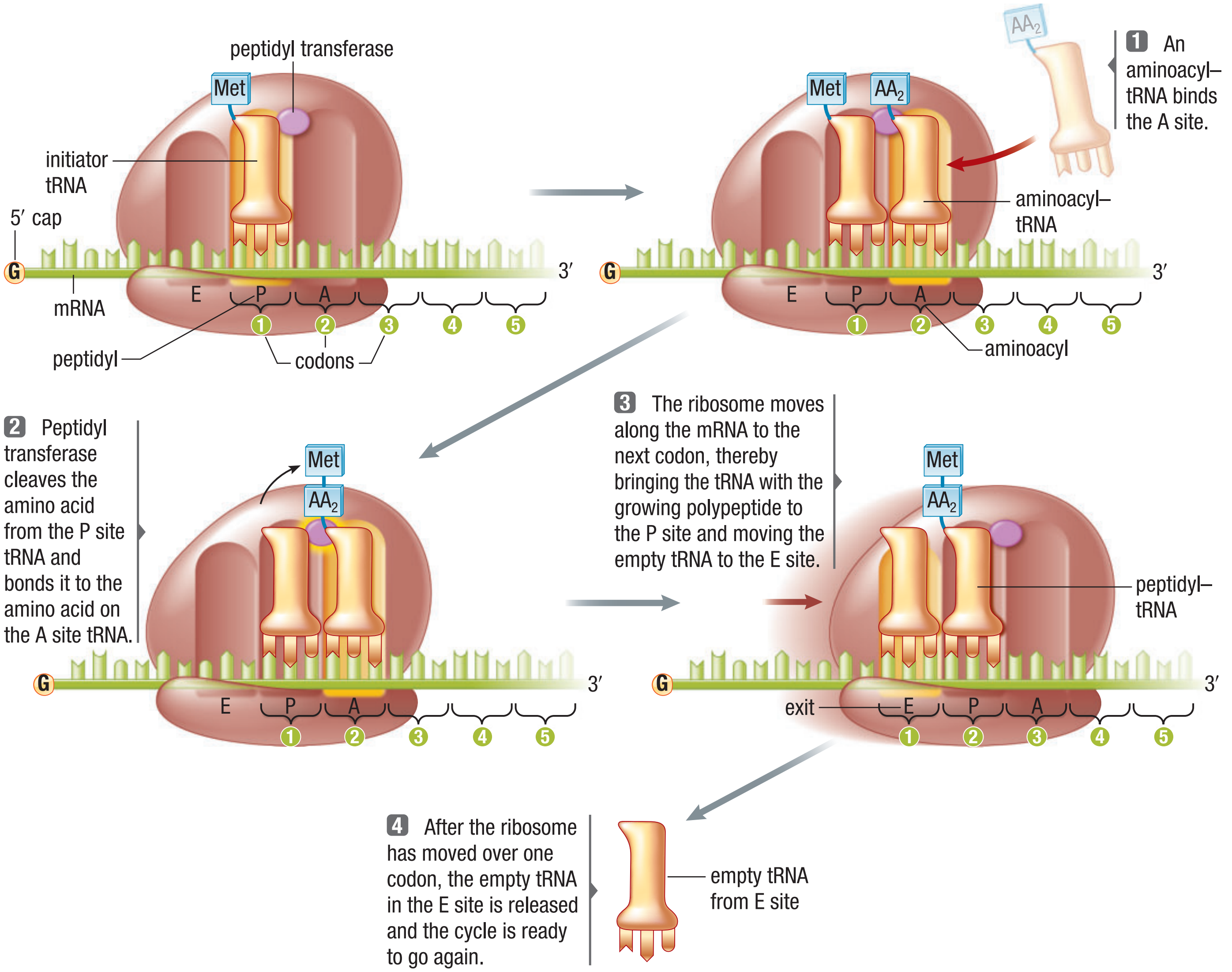
Figure 4 The steps in the initiation stage of translation in eukaryotes

After the initiator tRNA pairs with the AUG initiator codon, the subsequent stages of translation simply read the nucleotide bases, three at a time, on the mRNA. Since each codon consists of three bases, a sequence could potentially be read in three different ways, depending on where the ribosome begins. A correct initiator tRNA–AUG pairing establishes the correct **reading frame**: the series of codons for the polypeptide that is encoded by the mRNA.

reading frame a particular system for separating a base pair sequence into readable codons

Elongating the Polypeptide Chain

The central reactions of translation take place in the four steps of the elongation stage, which adds single amino acids sequentially to a growing polypeptide chain. **Figure 5** (next page) shows how the A, P, and E sites operate through the elongation stage. Elongation begins when an initiator tRNA, with its attached methionine, is bound to the P site in Step 1. The A site is empty.



1 An aminoacyl–tRNA binds the A site.

2 Peptidyl transferase cleaves the amino acid from the P site tRNA and bonds it to the amino acid on the A site tRNA.

3 The ribosome moves along the mRNA to the next codon, thereby bringing the tRNA with the growing polypeptide to the P site and moving the empty tRNA to the E site.

4 After the ribosome has moved over one codon, the empty tRNA in the E site is released and the cycle is ready to go again.

Figure 5 The steps in the elongation stage of translation

In Step 2, the second tRNA, with an appropriate anticodon and amino acid (AA_2), binds to the codon in the A site of the ribosome. A GTP rather than an ATP is hydrolyzed to provide free energy for this step. Next, the amino acid (Met) is cleaved from the tRNA in the P site and forms a peptide bond with the amino acid (AA_2) on the tRNA in the A site. This bond formation is catalyzed by peptidyl transferase, which is a ribosomal enzyme. At the end of Step 2, the new polypeptide chain is attached to the tRNA in the A site and an empty tRNA remains at the P site.

In Step 3, the ribosome moves along the mRNA to the next codon. The two tRNAs remain bound to their respective codons, so this step positions the newly formed peptidyl–tRNA in the P site and generates a vacant A site. An appropriate tRNA moves into the A site, and Steps 2 and 3 are repeated. After each repeat, the empty tRNA that was in the P site moves to the E site. In Step 4, the empty tRNA is released from the ribosome.

Termination of Protein Synthesis

Translation switches from the elongation to the termination stage when the A site of a ribosome arrives at one of the stop codons (UAA, UAG, or UGA) on the mRNA. When a stop codon appears at the A site, a protein release factor binds at this site instead of an aminoacyl–tRNA. In response, the polypeptide chain is released from the tRNA at the P site as usual. However, because no amino acid is present at the A site, the freed polypeptide chain is detached from the ribosome. At the same time, the ribosomal subunits separate and detach from the mRNA. The empty tRNA and the release factor are also released.

Investigation 7.3.1

Protein Synthesis (p. 354)
In this investigation, you will use your knowledge of transcription, translation, and the genetic code to analyze the genes and traits of a fictitious animal.

Protein Synthesis in Eukaryotes and in Prokaryotes

In both prokaryotes and eukaryotes, multiple ribosomes can translate an mRNA molecule at the same time, thereby increasing the production of crucial proteins (**Figure 6**). The complex that is formed is called a **polysome** (**Figure 7**).

polysome a complex that is formed when multiple ribosomes attach to the same mRNA molecule in order to facilitate rapid translation

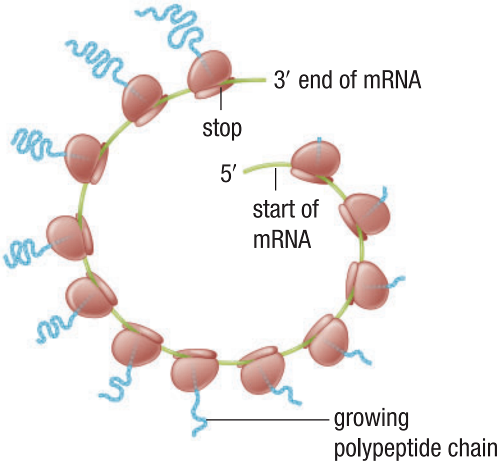


Figure 6 Polysomes consist of a series of ribosomes translating the same mRNA.

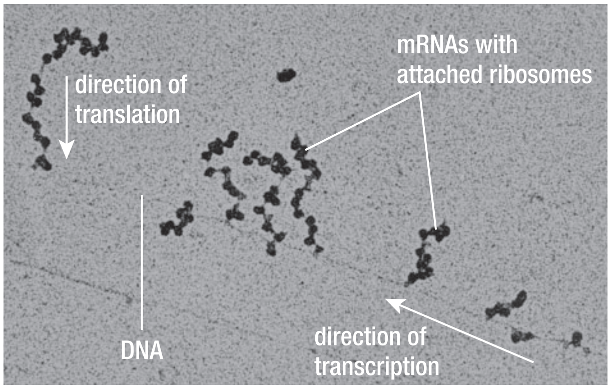


Figure 7 Simultaneous transcription and translation in progress in a prokaryotic cell. This electron microscope preparation was extracted from *E. coli* (magnified × 5 700 000).

In eukaryotes, polysomes only form outside the nucleus, in the cytosol. In prokaryotes, however, transcription and translation both occur in the cytosol. Thus the ribosomes have access to mRNA even as it is being synthesized. As a result, protein synthesis can occur at a much higher rate in prokaryotes than in eukaryotes. The tight coupling of transcription and translation also allows prokaryotes to rapidly synthesize proteins in response to changing environmental conditions. Other key differences are summarized in **Table 1**.

Table 1 A Comparison of Translation in Prokaryotes and Eukaryotes

Variable	Prokaryotes	Eukaryotes
location	• mRNA is translated by ribosomes in the cytosol as it is being transcribed from DNA	• mRNA can only be translated after exiting the nucleus to interact with ribosomes in the cytosol • some translation occurs in mitochondria and chloroplasts
initiation	• mRNA bases pair directly with a ribosomal binding site, just upstream of the start codon • mRNA 5′ cap is involved	• complex of Met–tRNA, with small ribosomal subunits, binds to an mRNA 5′ cap and scans until it encounters the start codon
elongation	• 15 to 20 elongation cycles per second	• 1 to 3 elongation cycles per second
termination	• stop codon appears and a release factor binds so that the polypeptide is released	
polysomes	• mRNA strand can be translated by multiple ribosomes simultaneously, even as it is being transcribed from DNA	• mRNA strand can be translated by multiple ribosomes simultaneously, but only in the cytosol

Polypeptide to Protein

The polypeptide that has been assembled by the ribosome is still not functional. The protein exists in an inactive state. Since the shape of a protein defines its function, the polypeptide chain must be folded into the correct conformation. Multiple processing reactions, carried out by specific enzymes, remove amino acids from the ends or interior of the chain and may add additional molecules, such as sugars, to the chain. These reactions activate the polypeptide, which then folds into its functional shape. In addition, many proteins are composed of two or more polypeptide chains. In these cases, the polypeptides produced from a number of separate translation events are processed and then assembled together to form a single functioning protein. This process of protein processing, from an inactive to an active state, is one of the many mechanisms that a cell uses to control the expression of its genes. You will learn more about gene expression in the next section.

Mini **Investigation**

Computer Simulation of Protein Synthesis

Skills: Performing, Observing, Analyzing, Evaluating, Communicating SKILLS HANDBOOK **A2.1**

In this investigation, you will transcribe DNA and translate the information into a polypeptide.

1. Connect to the Internet, and explore the protein synthesis simulation suggested by your teacher.
2. Follow the simulation instructions to model the steps of transcription and translation that take place during protein synthesis.
3. Carefully observe the actions of the many molecules involved and note the roles of various enzymes.

A. Compare the steps modelled in the computer simulation with those you have learned in Sections 7.2 and 7.3. K/U

B. List the codons that signal a ribosome to stop building a polypeptide chain. T/I

C. How would you change this simulation to make transcription and translation more understandable? T/I

D. Computer simulations are often used to help visualize a cellular process. Based on your experience with the simulation of protein synthesis, comment on the usefulness of this approach. Did the animation help you understand the process of protein synthesis? T/I

WEB LINK

7.3 Review

Summary

- Translation is the assembly of amino acids into polypeptides by a ribosome, using the information encoded in mRNA. This process has three stages: initiation, elongation, and termination. It is dependent on tRNA molecules.
- tRNA molecules are small RNA molecules. Each tRNA is associated with a specific amino acid, as dictated by its respective anticodon.
- An anticodon is a triplet of complementary bases that is able to bind to mRNA codons that code for the tRNA's specific amino acid.
- Initiation of translation is triggered by the large and small ribosome subunits binding to the 5′ cap of an mRNA molecule. The start codon is AUG, which corresponds to the amino acid methionine. The tRNA whose anticodon is UAC delivers methionine to the ribosome.
- Elongation involves building the polypeptide chain. Incoming tRNA molecules deliver the next appropriate amino acid to the ribosome, as dictated by the reading frame of three bases.
- Termination occurs when a stop codon is read by the ribosome. The stop codons are UAG, UGA, and UAA.
- More than one ribosome can translate an mRNA molecule at a time. The resulting structure is called a polysome.

Questions

1. What are the key steps in the initiation of translation in eukaryotes and prokaryotes? K/U
2. What is the role of tRNA in translation? K/U
3. Why is there not a specific tRNA molecule for each possible codon? K/U
4. List the possible anticodons for phenylalanine, alanine, and tyrosine. K/U
5. The wobble hypothesis states that there is increased flexibility in base pairing at the third nucleotide of some codons. Why does this not lead to frequent mistakes in the assembly of proteins? T/I
6. Explain what occurs at the A, P, and E sites during the translation of mRNA into a polypeptide. K/U
7. What are some examples of processes that might demand high rates of protein synthesis in humans? T/I
8. Using a diagram, summarize the process of translation. Label the areas of initiation, elongation, and termination. Present your diagram to a classmate, in a format of your choice. C
9. The set of all proteins expressed by a genome over the lifetime of a cell is called the proteome. The proteome is constantly changing as proteins interact with other proteins and chemical signals inside and outside the cell. Scientists are turning to proteomics—the study of the structure, activities, and functions of proteins—to understand the molecular basis of health and disease. Using the Internet or other sources, research the Proteome Project. Find out about its mission, the people and organizations involved, the technologies being used, and current findings. Present your findings in a format of your choice. CAREER LINK K/U C
10. Many proteins are assembled from more than one kind of polypeptide. A hemoglobin protein, for example, consists of two alpha and two beta polypeptides. In this case, two genes are needed to code for a single protein. Do online research to find examples of other proteins that are coded for by multiple genes. Summarize the information you find. A

WEB LINK

7.4 Controlling Gene Expression

insulin a hormone produced in the pancreas that lowers the blood glucose level by promoting the uptake of glucose by the body cells

Not all proteins are required by all cells at all times. It would be inefficient for a cell to transcribe and translate all its genes at all times. Rather, both prokaryotic and eukaryotic cells regulate gene expression in response to their own life cycles and environmental conditions. For example, human **insulin** is only required when the glucose level in the blood is high. Similarly, the *E. coli* enzyme that facilitates the breakdown of lactose is only transcribed and translated when the *E. coli* bacteria are exposed to lactose. The optimal functioning of an organism requires that genes be turned on and off as they are needed. Even though each cell contains the entire genome of an organism, cells know which genes to express and when. Intricate systems have evolved to fine-tune gene expression in both prokaryotes and eukaryotes. These systems ensure that all cells express only the genes they require, and that gene expression responds to the cellular environment.

Some proteins are always needed in a cell, and their genes are continuously transcribed and translated. Known as housekeeping genes, these genes regulate processes such as metabolism, growth, and DNA replication and transcription. The products of other, more specialized genes may be found only in certain types of cells or under particular environmental conditions. For example, liver cells require repair enzymes to manage the toxins in the body, and genes that produce hemoglobin molecules are transcribed and translated only in the cells that give rise to red blood cells.

In this section, you will learn about the mechanisms that cells use to regulate gene expression. Not only are these systems important to the biology of all organisms, but they also provide important tools that allow molecular biologists to manipulate the expression of eukaryotic genes by bacteria, viruses, and even cancer cells.

Prokaryotic Gene Control Mechanisms

Gene expression in prokaryotes is regulated in response to the concentrations of two molecules: lactose and tryptophan. Both of these responses are examples of negative feedback control.

The *Lac* Operon

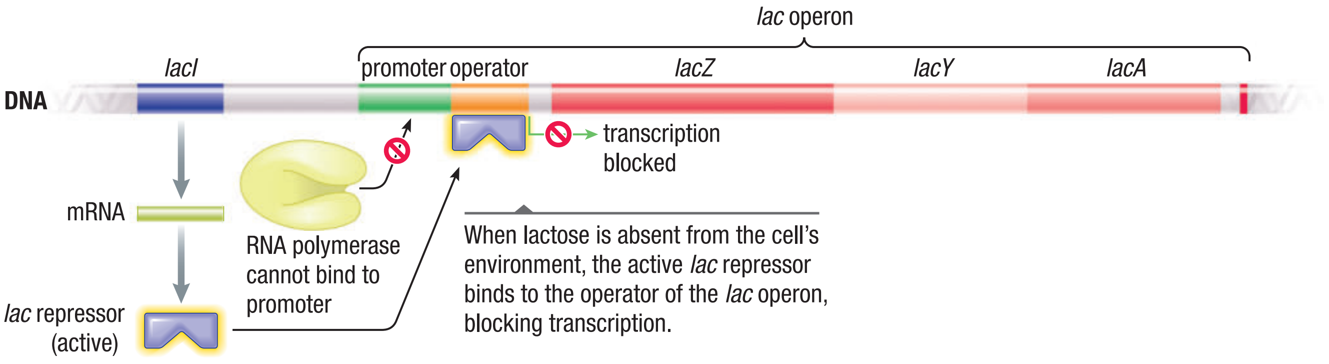
***lac* operon** a cluster of genes that contains the DNA sequences to regulate the metabolism of lactose

operator the region in the operon that regulatory factors bind to

repressor protein a protein that binds to the operator to repress gene transcription

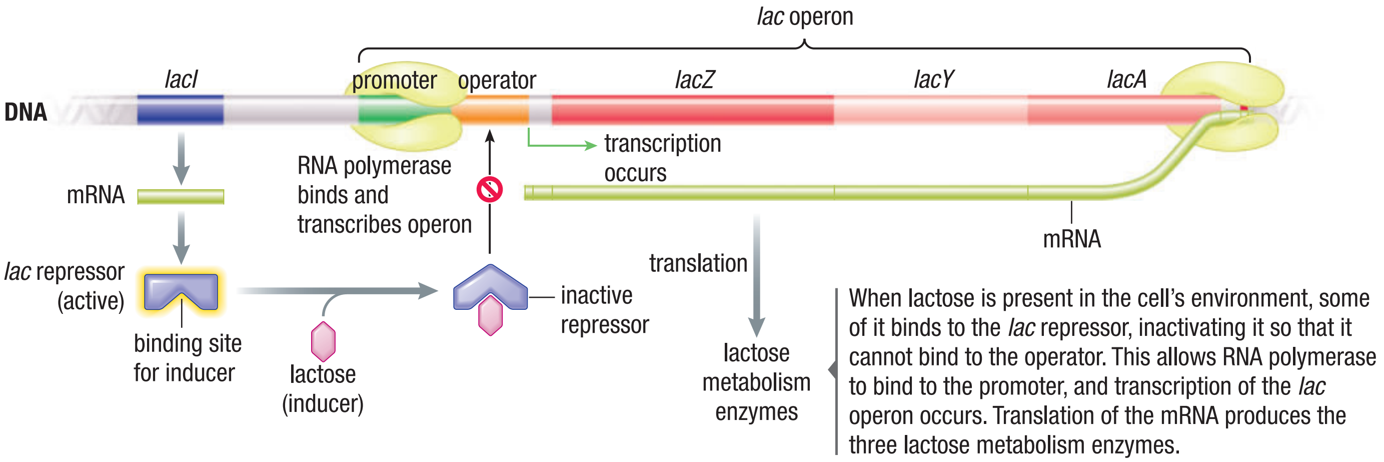
The sugar lactose, a potential source of energy for prokaryotes, must be acquired directly from the environment. To regulate the expression of the genes that are required for lactose metabolism, prokaryotes use what is known as the operon model of gene expression. The ***lac* operon** is a cluster of three genes that code for the proteins involved in the metabolism of lactose. The *lac* operon consists of a promoter (the site where DNA transcription begins), an **operator** (the sequence of bases that control transcription), and the coding regions for the various enzymes that actually metabolize the lactose. Upstream from the operon is a gene that codes for a **repressor protein**. This protein takes cues from the environment (in this case, the concentration of lactose within a cell) and regulates the production of the lactose-metabolizing proteins. For the *lac* operon, this protein is called the *lacI* protein or *lac* repressor. The genes that code for the *lac* repressor are always transcribed, so the *lac* repressor is always present within a cell. How this protein behaves, however, and the rate of synthesis of the other *lac* proteins, depends on the concentration of lactose in the cell.

In the absence of lactose, the *lac* repressor is active and binds to the operator (**Figure 1(a)**, next page). This keeps RNA polymerase from binding to the promoter region and stops the lactose-metabolizing enzymes from being synthesized. When lactose is present within a cell, some of it binds to a site on the *lac* repressor, rendering it inactive (**Figure 1(b)**, next page). The inactive *lac* repressor is unable to bind to the operator and block transcription. With the operator free of obstruction, RNA polymerase is able to bind to the promoter region, and transcription of the *lac* genes begins. The enzymes that metabolize lactose are then synthesized and start to break down the lactose in the cell. As the concentration of lactose in the cell decreases, the amount of inactivated *lac* repressor decreases (that is, there is less and less lactose to deactivate the *lac* repressor). Eventually, the reactivated *lac* repressor again binds to the operator, stopping transcription.



When lactose is absent from the cell's environment, the active *lac* repressor binds to the operator of the *lac* operon, blocking transcription.

(a) lactose absent from cell's environment



When lactose is present in the cell's environment, some of it binds to the *lac* repressor, inactivating it so that it cannot bind to the operator. This allows RNA polymerase to bind to the promoter, and transcription of the *lac* operon occurs. Translation of the mRNA produces the three lactose metabolism enzymes.

(b) lactose present in cell's environment

Figure 1 Regulation of the *lac* operon in prokaryotes by the (a) absence and (b) presence of lactose

Note that the lactose itself acts as a signal molecule, telling the cell when to synthesize the lactose-metabolizing enzymes. This type of signal molecule is called an **inducer**, since it serves to initiate the production of enzymes. The *lac* operon is known as an inducible operon because the inducer inactivates the repressor and allows the gene to be transcribed. There is a direct correlation between the amount of lactose in a cell and the rate at which the *lac* enzymes are synthesized. As the concentration of lactose in the cell increases or decreases, so too does the transcription of the *lac* genes. This is an important way for the cell to conserve energy, by not synthesizing proteins when they are not necessary.

inducer a signal molecule that triggers the expression of an operon's genes

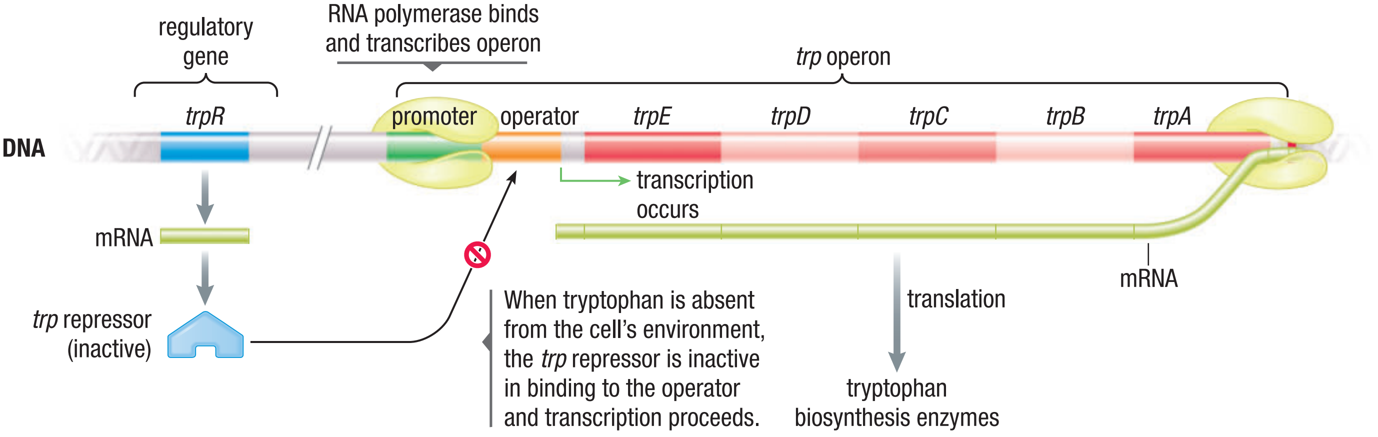
The *trp* Operon

Tryptophan is an important amino acid that is used to build proteins. Most prokaryotic cells are able to synthesize tryptophan independently, but they can also take it up directly if it is available in the environment. The operon that regulates the production of tryptophan in a cell is called the *trp* operon.

The *trp* operon has the same structure as the *lac* operon: a promoter and an operator that precede the genes coding for tryptophan-synthesizing enzymes. There is also a gene that codes for a *trp* repressor protein. This repressor protein is always synthesized (like in the *lac* operon), but the difference is in how the repressor protein acts to regulate the expression of the tryptophan enzymes. Whereas the *lac* repressor protein is inactivated by a signal molecule, the *trp* repressor protein is activated in the presence of tryptophan.

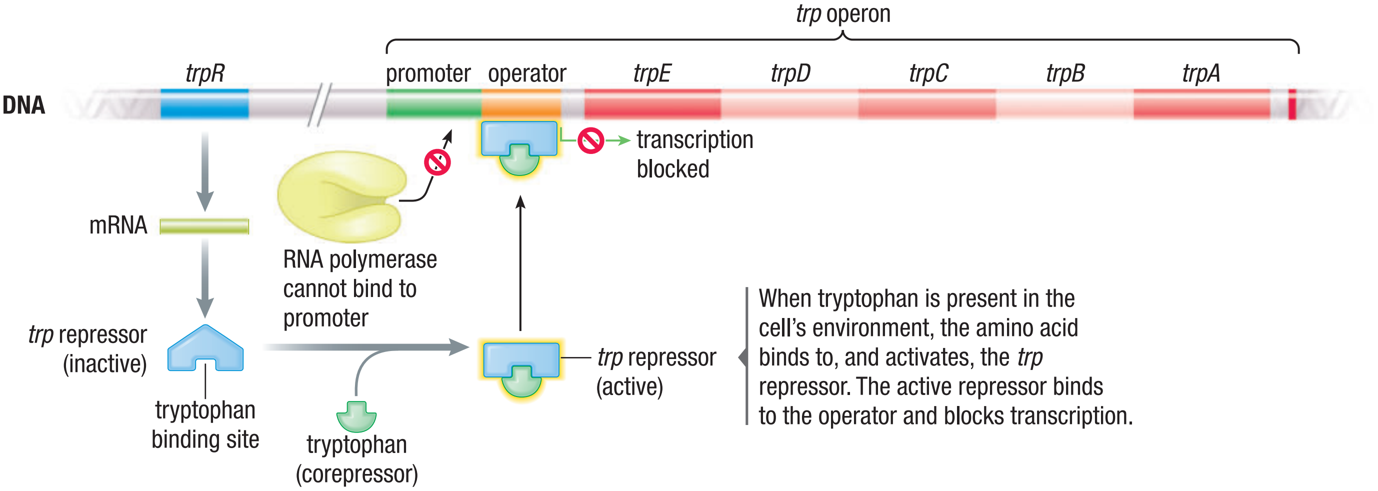
When tryptophan is not present in the environment, the repressor protein is in an inactive state and does not bind to the operator (**Figure 2(a)**). RNA polymerase is able to bind to the promoter region, and the transcription of the genes that are responsible for the biosynthesis of tryptophan can proceed. When tryptophan is present in the environment, the cell can conserve energy by using the available tryptophan and stopping the transcription of the genes that code for the enzymes involved in the biosynthesis of the amino acid (**Figure 2(b)**). Tryptophan acts as a signal molecule and activates the repressor protein. The activated repressor protein is then able to bind to the operator and stop transcription of the tryptophan-synthesizing genes. When a signal molecule functions in this way, it is called a **corepressor**: it serves to repress (rather than induce) the expression of a set of genes. As the concentration of environmental tryptophan decreases, the repressor proteins become deactivated and the tryptophan-synthesizing genes are transcribed. This negative correlation between the amount of tryptophan in the environment and the rate of tryptophan synthesis is an example of a negative feedback mechanism.

corepressor a signal molecule that binds to a regulatory protein to reduce the expression of an operon's genes



When tryptophan is absent from the cell's environment, the *trp* repressor is inactive in binding to the operator and transcription proceeds.

(a) tryptophan absent from cell's environment



When tryptophan is present in the cell's environment, the amino acid binds to, and activates, the *trp* repressor. The active repressor binds to the operator and blocks transcription.

(b) tryptophan present in cell's environment

Figure 2 Regulation of the *trp* operon by the (a) absence and (b) presence of tryptophan

Eukaryotic Gene Control Mechanisms

Eukaryotic gene expression requires a larger number of steps. Therefore, the methods for regulating eukaryotic gene expression are more complex than the methods for regulating prokaryotic gene expression. Eukaryotes do not use the operon system just described.

Instead, the control mechanisms in eukaryotes fall into four categories:

- transcriptional (as mRNA is being synthesized)
- post-transcriptional (as mRNA is being processed)
- translational (as the protein is being synthesized)
- post-translational (after the protein has been synthesized)

Transcriptional Regulation

Although eukaryotic gene regulation occurs at multiple levels, the most common type of regulation occurs during transcription. You may remember from Chapter 6 that in eukaryotic chromatin, the DNA is wrapped around histone proteins. Therefore, the gene promoters are not accessible to the proteins that initiate transcription. This configuration keeps the gene promoters inactive. For a gene to be transcribed, the chromatin must be partially unwound to expose the promoter.

In one type of transcriptional regulation, the promoter is exposed when an activator molecule binds to a sequence that is upstream of the gene's promoter and signals a protein remodelling complex (**Figure 3**). As a result, the histone core proteins are displaced from the DNA (chromatin remodelling), exposing the promoter. In another type of transcriptional regulation, an activator molecule is bound to a regulatory sequence upstream of the gene to be transcribed. This signals an enzyme that can add an acetyl group (CH_3COO^-) to histones. The addition of the acetyl group to histones loosens their association with DNA, and the promoter becomes accessible.

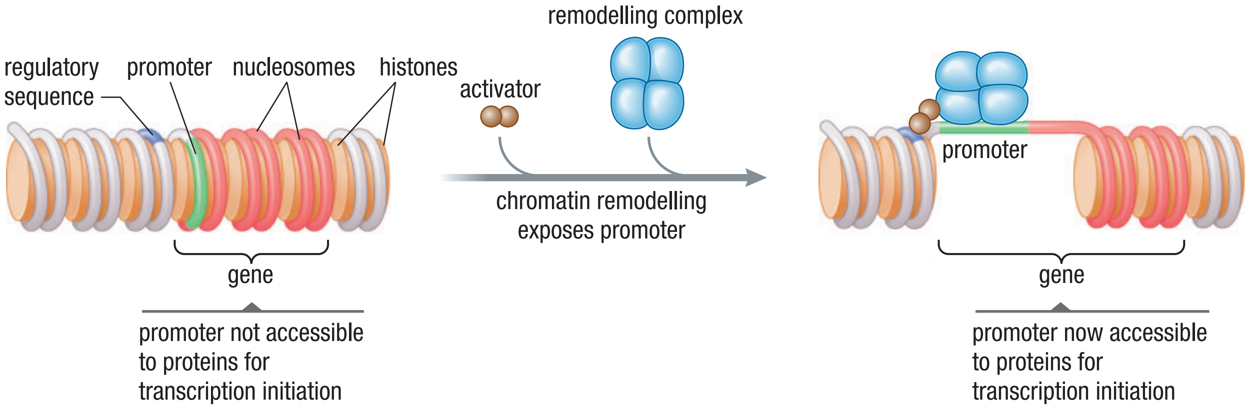
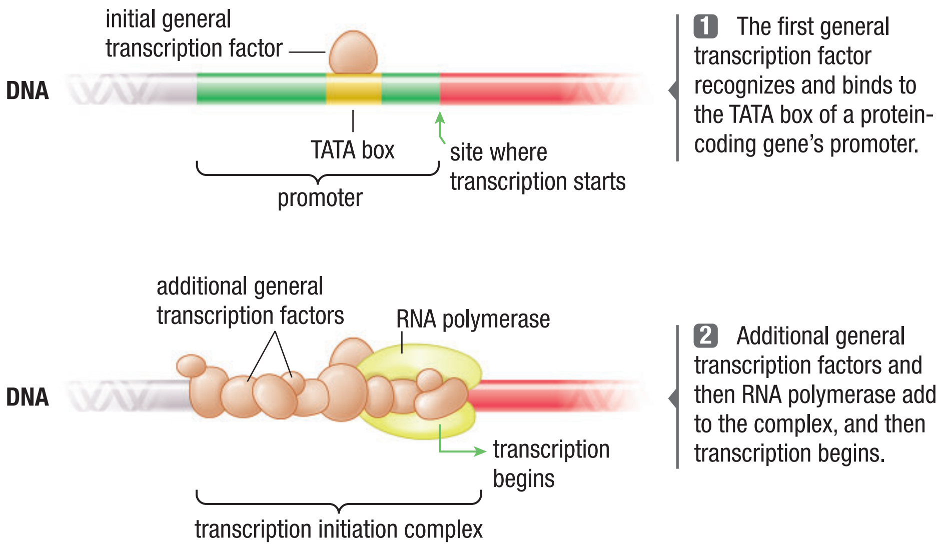

remodelling complex
regulatory sequence
promoter
nucleosomes
histones
activator
chromatin remodelling exposes promoter
promoter
gene
promoter not accessible to proteins for transcription initiation
gene
promoter now accessible to proteins for transcription initiation

Figure 3 A chromatin remodelling complex exposes the promoter, and thus enables transcription.

To initiate transcription, a series of proteins, called general transcription factors, accumulate on the promoter. They bind to a specific region of the promoter (TATA box) and provide a substrate that the RNA polymerase can bind to and thus begin transcription (**Figure 4**, next page). Together, the general transcription factors and RNA polymerase form the transcription initiation complex. This establishes a base rate of gene transcription, which can be further altered by additional proteins called activators and repressors, depending on the needs of the cell. The activators and repressors (like the regulatory proteins in the *lac* and *trp* operons) attach themselves to the promoter to increase or decrease the rate of transcription.

Another method of eukaryotic gene regulation that is important for biotechnology applications is methylation. A methyl group ($-CH_3$) is added to the cytosine bases in the promoter of a gene, inhibiting transcription. This effect is called silencing.


initial general transcription factor
DNA
TATA box
site where transcription starts
promoter
additional general transcription factors
RNA polymerase
DNA
transcription begins
transcription initiation complex

1 The first general transcription factor recognizes and binds to the TATA box of a protein-coding gene's promoter.

2 Additional general transcription factors and then RNA polymerase add to the complex, and then transcription begins.

Figure 4 General transcription factors accumulate on the promoter to initiate transcription.

Methylation is another way to put genes or entire regions of chromosomes "on hold" until they are required. For example, the genes that code for the production of hemoglobin are in an inactive, methylated state in almost all the body cells. However, the cells in bone marrow, which produce red blood cells, use specific enzymes to remove the methyl groups and allow transcription.

An example of the power of gene methylation is seen in agouti mice. Mice whose agouti genes have been turned on can look entirely different in both colour and size, even though they are genetically identical. One mouse may be small and brown, while its twin may be obese and yellow (**Figure 5**). In normal, healthy mice, the agouti genes are kept in the "off" position (silenced). Methyl groups are attached to the corresponding regions of DNA, and transcription is prevented. In yellow and/or obese mice, however, the same genes are not methylated. Thus, these genes are expressed or "turned on." Mice whose agouti gene is "on" have a higher risk of cancer and diabetes.

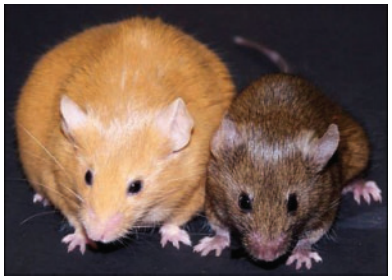


Figure 5 A mouse whose agouti genes have been turned on (left) is very different from a mouse whose agouti genes have been silenced.

A number of environmental triggers have been shown to contribute to the agouti gene promoter being methylated or not methylated. One suspected trigger is a chemical called bisphenol A, which, until recently, was found in many plastic bottles, including baby bottles. Researchers exposed pregnant mice to bisphenol A and watched as more of their offspring developed into yellow, obese mice than would normally be expected. These results supported the hypothesis that exposure to bisphenol A results in demethylation, the removal of methyl groups from DNA. However, not all the offspring grew up to be obese. Researchers concluded that bisphenol exposure did not guarantee obesity in mice, but simply increased the risk of developing obesity. The silencing effect is used by researchers who wish to test the effects of a single gene. Once the coding sequence is located, they can methylate the gene and observe the effect of its absence on the organism they are studying.

Post-transcriptional Regulation

Post-transcriptional regulation influences gene expression by several mechanisms, including changes in pre-mRNA processing and the rate at which mRNAs are degraded. Alternative splicing is one example of post-transcriptional regulation. Alternative splicing produces different mRNAs from pre-mRNA by removing different combinations of introns. The remaining exons are spliced together (Section 7.2). Depending on which protein is required by the cell, an intron in one pre-mRNA may be considered an exon in another pre-mRNA and may therefore not be spliced out of the second pre-mRNA transcript. The resulting mRNAs are translated to produce a family of related polypeptides and their associated final proteins with various combinations of amino acid sequences. Alternative splicing is a powerful tool, which is used by cells to optimize the production of different proteins depending on cell type. Perhaps 75 % of human genes are alternatively spliced at the pre-mRNA level.

Another example of post-transcriptional regulation involves binding masking proteins to mRNA. When the mRNA is associated with a masking protein, it does not undergo protein synthesis. Masking proteins are a common form of control in many animal eggs, keeping mRNAs in an inactive form until an egg has been fertilized and embryonic development is underway. When it is time for the mRNA to be translated, other proteins remove the masking proteins.

A third example of post-transcriptional regulation changes the rate of degradation of mRNAs. A regulatory molecule, such as a hormone, will directly or indirectly affect the rate of mRNA breakdown. For example, in the mammary gland of a rat, it takes about 5 h for half of the mRNA for casein (a milk protein) to break down. In the presence of the hormone prolactin, the time increases to 92 h. Prolactin is a hormone that is synthesized in the brain and the mammary glands. When a large amount of casein is needed for milk production, there is an abundant supply of prolactin and the lifespan of the casein mRNA is extended.

Translational Regulation

Translational regulation occurs during protein synthesis by a ribosome. One important mechanism changes the length of the poly(A) tail of the mRNA molecules. Specific enzymes can add or delete repeating sequences of adenine at the ends of the mRNA molecules. This change in the length of the poly(A) tail may increase or decrease the time that is required to translate the mRNA into a protein. Scientists do not completely understand how this mechanism functions, but they think that the cell may take cues from the environment or intracellular molecules to adjust the rate at which certain mRNA molecules are translated.

Post-translational Regulation

After the mRNA is translated and proteins are synthesized, the cell can still regulate expression by limiting the availability of functional proteins. Three methods are used: processing, chemical modification, and degradation.

When proteins are initially synthesized, they are in an inactive form and must be activated by various processing mechanisms. Insulin (which regulates the level of glucose in the blood) is initially synthesized as proinsulin, an inactivated precursor. A processing mechanism removes specific sections of the protein and renders it active. The cell can regulate these types of processing mechanisms to control the availability of activated proteins and thus regulate the end product of certain genes.

During the chemical modification of a protein, certain chemical groups that are attached to the protein are added or deleted, affecting its function. The presence or absence of these chemical groups puts the protein “on hold” until it is needed. Once environmental and cellular conditions are sufficient, the groups are added or removed and the protein can carry out its function.

Like most other biosynthesized molecules, proteins are subject to constant degradation both inside and outside the cell. Some proteins are used for only a few minutes before they are broken down, while others can last the entire lifetime of an organism. This rate of degradation is under regulatory control, modifying the rate at which the products of gene expression are available. Short-lived proteins are tagged with a small protein called ubiquitin, which is recognized by the degradation mechanisms of the cell. Adding or removing these tags can either shorten or extend the functional life of a protein. The degraded proteins are broken down into their constituent amino acids and recycled to synthesize new proteins.

Table 1 summarizes the gene control mechanisms in eukaryotic cells.

Table 1 Four Levels of Control of Gene Expression in Eukaryotic Cells

Type of control	Description	Specific examples
transcriptional	regulates which genes are transcribed (DNA to mRNA) or controls the rate at which transcription occurs	• Access to promoters is provided by loosening a DNA molecule from histones. • Activator and repressor proteins bind to the promoter and enhance or decrease the rate of transcription. • Methyl groups are added to cytosine bases in the promoter. RNA polymerase cannot bind and transcribe.
post-transcriptional	controls the availability of mRNA molecules to ribosomes; pre-mRNA molecules undergo changes in the nucleus, resulting in final mRNA before translation occurs	• Alternative splicing occurs. Different combinations of introns are removed, and the remaining exons are spliced together. • Masking proteins bind to mRNA and inhibit further processing. • The rate of degradation of mRNA is dependent on the need of the cell for the gene product.
translational	controls how often and how rapidly mRNA transcripts will be translated into proteins	• Variation of the length of the poly(A) tail is related to the rate of translation.
post-translational	controls when proteins become fully functional, how long they are functional, and when they are degraded	• Processing occurs. The polypeptide is chemically modified to render it an active protein. • The presence of hormones may lengthen or shorten the length of time that a protein is functional. • Ubiquitin-tagged proteins are degraded.

Cancer

Cancer cells lack the regulatory mechanisms that keep healthy cells under control. The constant lengthening of telomeres is one way that cancer cells can grow out of control (Sections 6.5 and 6.6). This phenomenon (like all aspects of a cell's function) is controlled by gene expression. Some mutations in a cell's genome can have negative or even deadly effects on the organism. The probability that a given sequence of DNA has experienced a mutation increases over the lifespan of an organism. Every exposure to a potential mutagen (such as radiation or smoke), no matter how small, has a cumulative effect on the number of mutations in the genome. This is why many forms of cancer occur most often during old age, after the genome has accumulated mutations that can affect cellular functions. A mutation in one cell is passed on only to that cell's daughter cells, not to any other cells in the organism.

If a cell begins to deviate from normal cell division, it can produce a mass of undifferentiated cells called a tumour. If this mass of cells grows slowly, remains in place, and does not return once it has been removed, it is called a benign tumour. Benign tumours are usually not life-threatening. If the cells grow uncontrollably, invade surrounding tissue, and begin to affect the functions of the organism, they are called malignant tumours or cancers (**Figure 6**). Malignant tumours are more difficult to remove from the body, and measures such as chemotherapy and radiation are required.

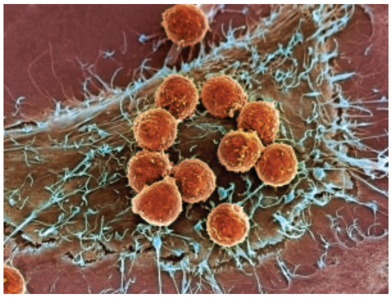


Figure 6 White blood cells attacking a cancerous cell in the human body

The unchecked growth and indefinite lifespan of cancer cells are the result of changes in gene regulation. The usual mechanisms and signals that allow healthy cells to express their genes properly have little to no effect on cancerous cells, and this is reflected in certain specific mutations that arise in most tumours. Healthy cells contain a set of genes that code for various proteins that stimulate cell growth. In cancerous cells, these genes are mutated to become oncogenes. Oncogenes cause the constant and undifferentiated cell division that creates tumours.

Changes in gene regulation can arise from mutations in the promoters, mutations in the coding regions that affect the functions of the protein, or the introduction of foreign DNA from viruses (Section 7.7). The mutations that give rise to cancer cells may seem like exceptions, but it is just as exceptional that most of an organism's genes are regulated almost perfectly throughout its entire life.

7.4 Review

Summary

- A cell responds to changes in its environment by regulating the rate at which its genes are expressed.
- Prokaryotes use operons to regulate gene expression. An operon is a section of DNA that includes a promoter, an operator, a regulatory protein, and the sequence of genes that code for one or more specific proteins.
- The *lac* operon uses a signal molecule (lactose) that induces the expression of the operon's genes, whereas the *trp* operon uses a signal molecule (tryptophan) that represses the expression of the operon's genes.
- Gene regulation in eukaryotes can occur during transcription, post-transcription, translation, or post-translation.
- Transcriptional control regulates which genes are transcribed and/or the rate at which transcription occurs.
- Forms of post-transcriptional control include alternative splicing of exons and introns, masking proteins binding to mRNA, and the rate of degradation of mRNA.
- Translational control involves how often and how rapidly an mRNA is translated.
- Post-translational control regulates when proteins become fully functional, how long they are functional, and when they are degraded.
- Cancerous cells lack the regulatory mechanisms that allow healthy cells to grow and express their genes properly.

Questions

1. Define the following terms:
   (a) operon
   (b) operator
   (c) corepressor
   (d) repressor
   (e) housekeeping genes
   (f) inducer K/U
2. Why do eukaryotes have a more complex system of gene regulation than prokaryotes? Use an example to explain your reasoning. T/I
3. What features do the *lac* and *trp* operons have in common? How do these operons differ? T/I
4. How does the *lac* operon regulate the production of the enzymes needed to metabolize lactose? Summarize the key ideas and concepts in list format. K/U C
5. Describe the *trp* operon system if the level of tryptophan is low. Include the activities and states of all the major enzymes and proteins found in the system. What changes take place if tryptophan is suddenly made available as a nutrient to the bacteria? K/U
6. Give an example of a eukaryotic regulatory mechanism that occurs
   (a) during transcription
   (b) during translation
   (c) after translation K/U
7. Eukaryotic transcription is generally controlled by the binding of regulatory proteins to DNA sequences, rather than by the modification of RNA polymerases. Develop a hypothesis that explains the reason for this. T/I
8. The twin mice in Figure 5 (page 336) have one small but important difference in their agouti gene. What is the relationship between the phenotype of the agouti mouse (left in the photograph) and chemicals such as bisphenol-A? T/I
9. Discuss what happens to cells to cause them to become cancerous. K/U

7.5 Genetic Mutations

WARNING
CIGARETTES CAUSE MOUTH DISEASES
Cigarette smoke causes oral cancer, gum diseases and tooth loss.
Health Canada

Figure 1 Cigarette labels clearly describe the negative consequences of smoking.

Over the years, legislation has forced cigarette manufacturers to print warnings on their packages about the dangers of smoking (**Figure 1**). What if the following warning was placed on a cigarette package: "Smokers with a particular mutation have a higher risk of developing cancer." If you were a smoker, would you be concerned that you might have this mutation? Would you get tested for it or stop smoking? If you knew about any mutation in your genome, would you alter your lifestyle choices?

Genetic mutations are changes in the DNA sequence, caused by various mechanisms. For example, synthetic chemicals, radiation, incorrect replication, and random mutations can change the structure and function of the genome. Mutations caused by smoking increase the risk of various forms of cancer. A region on human chromosome 15 is known to play a part in an individual's susceptibility to developing lung cancer. If mutated, this region increases a smoker's risk of lung cancer by 30 to 80 %, depending on whether the smoker has one or two copies of the 15q24 susceptibility locus. A susceptibility locus is a region on a given chromosome where mutations that affect one or more genes are more likely to be present, based on statistical evidence.

The word "mutation" has developed a negative connotation. However, it is important to remember that mutations have given rise to the variety of life that we see today. The current inhabitants of Earth are a result of many mutations over time—the products of natural selection. In this section, you will look at the different types of mutations and learn how these mutations affect the functions of genes and the synthesis of proteins.

Small-Scale Mutations

Small-scale mutations include mutations of an individual base pair, called **point mutations**, and of small groups of base pairs. There are several different types of point mutations, including

- the **substitution** of one base for another
- the **insertion** or **deletion** of a single base pair
- the **inversion** of two adjoining base pairs

Small-scale mutations of a small group of base pairs are categorized similarly: the substitution, insertion, or deletion of the group.

As a result of a point mutation, either a substitution or a deletion mutation, individuals with β-thalassemia cannot synthesize β-globin. Part of normal hemoglobin, β-globin is 146 amino acids in length. The mutated gene codes for a stop codon in the position of codon 39. Because β-globin is absent, individuals with β-thalassemia have small erythrocytes that rupture easily. These people often require blood transfusions.

The differences in the DNA of individuals within a population that are caused by point mutations are referred to as **single nucleotide polymorphisms** or **SNPs** (pronounced "snips"; *poly* means "many" and *morphisms* means "alternative forms"). In other words, population X may have 120 known SNPs in allele Y. Because SNPs are particularly common and variable in non-coding parts of the genome, they are sometimes used in forensics and paternity testing.

The effects of small-scale mutations can range from being positive, through having no effect, to being severe. Functionally, small-scale mutations can be categorized into four groups: missense mutations, nonsense mutations, silent mutations, and frameshift mutations. These are described in **Figure 2** (next page).

point mutation a change in a single nucleotide within a gene

substitution the replacement of one base pair in a DNA sequence by another base pair

insertion the addition of a base pair (small-scale mutation) or larger coding region (large-scale mutation) to a DNA sequence

deletion the removal of a base pair (small-scale mutation) or larger coding region (large-scale mutation) from a DNA sequence

inversion two adjacent bases trading places (small-scale mutation) or the reversal of a sequence of DNA (large-scale mutation)

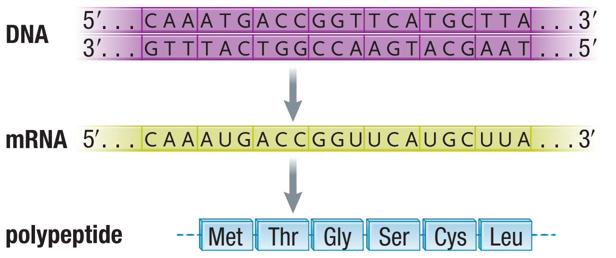
single nucleotide polymorphism (SNP) a difference in the DNA between individuals caused by point mutations

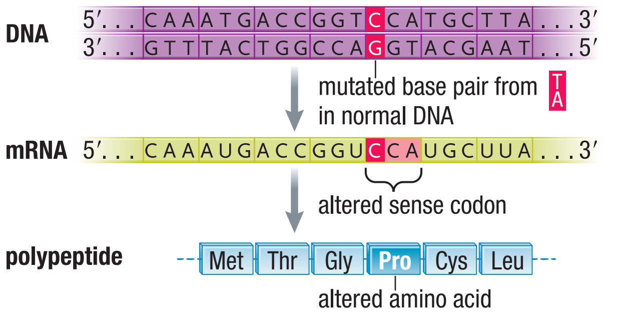
missense mutation a mutation that changes a single amino acid in the coding sequence

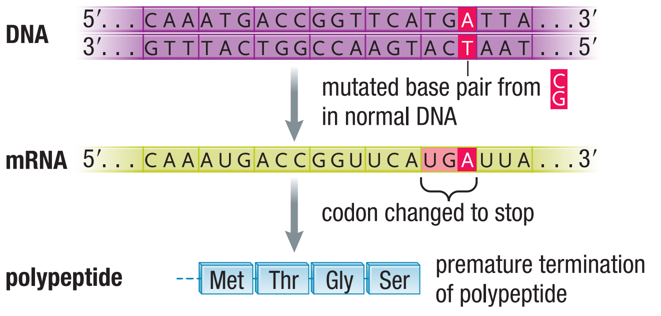
nonsense mutation a mutation that results in a premature stop codon

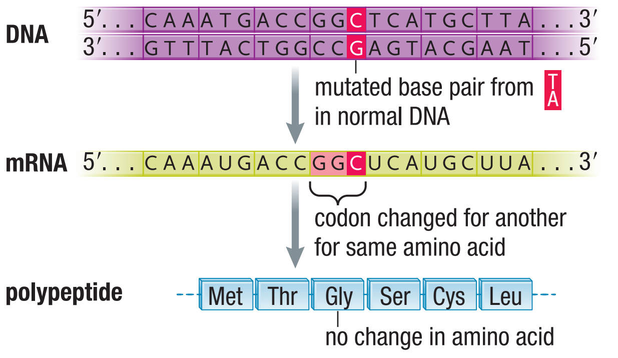
silent mutation a mutation that does not alter the resulting sequence of amino acids

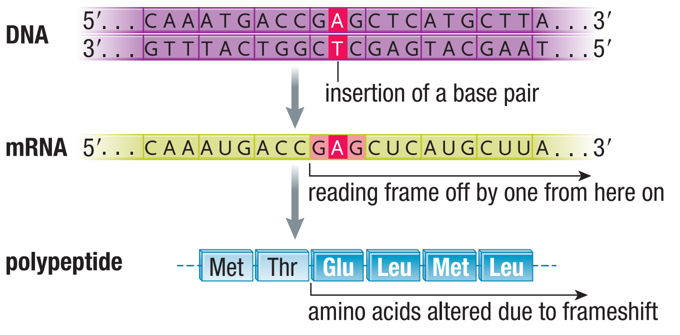
frameshift mutation a shift in the reading frame resulting in multiple missense and/or nonsense effects

<table>
<tr><th>Mutation and description</th><th>Illustration</th></tr>
<tr><td>No mutation: This is the normal condition.</td><td>
DNA
5′. . . CAAATGACCGGTTCATGCTTA. . .3′
3′. . . GTTTACTGGCCAAGTACGAAT. . .5′
mRNA
5′. . . CAAAUGACCGGUUCAUGCUUA. . .3′
polypeptide
Met
Thr
Gly
Ser
Cys
Leu

</td></tr>
<tr><td>A missense mutation occurs when a change of a single base pair or group of base pairs results in the code for a different amino acid. The protein that is synthesized will have a different sequence and structure, and it may be non-functional or function differently. A missense mutation can be beneficial if it creates a new, desirable effect.</td><td>
DNA
5′. . . CAAATGACCGGTCCATGCTTA. . .3′
3′. . . GTTTACTGGCCAGGTACGAAT. . .5′
mutated base pair from T A in normal DNA
mRNA
5′. . . CAAAUGACCGGUCCAUGCUUA. . .3′
altered sense codon
polypeptide
Met
Thr
Gly
Pro
Cys
Leu
altered amino acid

</td></tr>
<tr><td>A nonsense mutation occurs when the change of a single base pair or group of base pairs results in a premature stop code in the gene. The polypeptide is cut short and, most likely, will be unable to function.</td><td>
DNA
5′. . . CAAATGACCGGTTCATGATTA. . .3′
3′. . . GTTTACTGGCCAAGTACTAAT. . .5′
mutated base pair from C G in normal DNA
mRNA
5′. . . CAAAUGACCGGUUCAUGAUUA. . .3′
codon changed to stop
polypeptide
Met
Thr
Gly
Ser
premature termination of polypeptide

</td></tr>
<tr><td>A silent mutation occurs when the change in one or more base pairs does not affect the functioning of the gene. The mutated DNA sequence codes for the same amino acid as the non-mutated sequence, and the resulting protein is not altered.</td><td>
DNA
5′. . . CAAATGACCGGCTCATGCTTA. . .3′
3′. . . GTTTACTGGCCGAGTACGAAT. . .5′
mutated base pair from T A in normal DNA
mRNA
5′. . . CAAAUGACCGGCUCAUGCUUA. . .3′
codon changed for another for same amino acid
polypeptide
Met
Thr
Gly
Ser
Cys
Leu
no change in amino acid

</td></tr>
<tr><td>A frameshift mutation occurs when one or more nucleotides are inserted into or deleted from a DNA sequence, causing the reading frame of codons to shift in one direction or the other. This results in multiple missense and/or nonsense effects. The frameshift mutation “shifts” the reading frame by one or more steps, and every amino acid coded for after this mutation is affected. Any deletion or insertion of base pairs in multiples of three does not cause frameshifts because the reading frame is unaltered. Tay-Sachs disease is a result of the insertion of four base pairs.</td><td>
DNA
5′. . . CAAATGACCGAGCTCATGCTTA. . .3′
3′. . . GTTTACTGGCTCGAGTACGAAT. . .5′
insertion of a base pair
mRNA
5′. . . CAAAUGACCGAGCUCAUGCUUA. . .3′
reading frame off by one from here on
polypeptide
Met
Thr
Glu
Leu
Met
Leu
amino acids altered due to frameshift

</td></tr>
</table>

Figure 2 Types of mutations in a DNA sequence and how they affect the mRNA and protein sequences

Large-Scale Mutations

Large-scale mutations can involve multiple nucleotides, entire genes, or whole regions of chromosomes. Like point mutations, large-scale mutations can have various effects on the organization of a genome and the functioning of the organism. Amplification, also known as gene duplication, occurs when a gene or group of genes is copied to multiple regions of chromosomes. This duplication leads to a larger number of copies of the gene or group of genes, which compounds its effects. An important biological implication of amplification is the creation of opportunities for new genes with new functions to evolve. The original gene function is retained by one gene, but the copies are subjected to further mutations, which may be selected for by nature.

In large-scale deletions, entire coding regions of DNA are removed. Unless multiple copies of a gene are available, this large loss of genetic material may negatively affect the functioning of a cell. Dystrophin is a protein that is an important component of skeletal muscle. Deletion of all or part of the dystrophin gene results in Duchenne muscular dystrophy. Individuals with this mutation usually die in their early 20s due to weak respiratory muscle. If a small part of this gene is deleted, Becker muscular dystrophy results. Individuals with Becker muscular dystrophy have weak muscles but live an almost normal life.

translocation the movement of entire genes or sequences of DNA from one chromosome to another

Chromosomal **translocation** occurs when entire genes or groups of genes are moved from one chromosome to another. Translocation between two non-homologous chromosomes usually occurs when portions of each chromosome break off and exchange places. If a DNA coding sequence is translocated adjacent to another coding sequence, this can result in an entirely new gene and a completely novel polypeptide chain. Certain sequences of DNA, called transposable elements, move freely about the genome. If transposable elements are inserted near an existing gene sequence, they can enhance, disrupt, or otherwise modify the expression of the gene.

Inversion occurs when a portion of a DNA molecule, often containing one or many genes, reverses its direction in the genome. This does not directly result in the loss of genetic material. However, if the break occurs in the middle of a coding sequence, the gene may be compromised.

A trinucleotide is a triplet of nucleotides. An example of a trinucleotide repeat is CAG CAG CAG CAG. Trinucleotide repeats are normal in the genome. Sometimes a mutation occurs, and these repeats become unstable and expand uncontrollably. This mutation, known as trinucleotide repeat expansion, increases in the number of repeats from one generation to the next. Huntington's disease arises from a trinucleotide repeat.

Causes of Genetic Mutations

spontaneous mutation a mutation that is caused by an error in DNA replication

induced mutation a mutation that is caused by an environmental agent

mutagen an environmental agent that directly alters the DNA within a cell

Mutations can be grouped into two categories: spontaneous mutations and induced mutations. **Spontaneous mutations** arise from inaccurate DNA replication. Recall that genomes use a comprehensive quality control system to ensure that DNA is replicated as accurately as possible. However, there is still the possibility of errors during replication. **Induced mutations** are caused by an environmental agent, known as a **mutagen**, that directly alters the DNA within a cell. A mutagen can enter the cell nucleus and directly access the genome. Two of the most common forms of mutagens are chemicals and radiation (**Figure 3**, next page). Both spontaneous and induced mutations can take the form of either small-scale or large-scale mutations. Every subsequent round of cell division can compound the effects of a mutation. WEB LINK

Chemical Mutagens

A chemical mutagen is any chemical agent that can enter the cell nucleus and chemically alter the structure of the DNA. Carbon monoxide, found in exhaust fumes and tobacco smoke, acts as a mutagen and is linked to various forms of cancer. Some chemical mutagens, such as nitrous acid, can modify individual nucleotides so that the nucleotides resemble other base pairs. This type of mutation confuses the replication machinery and results in inaccurate copying.

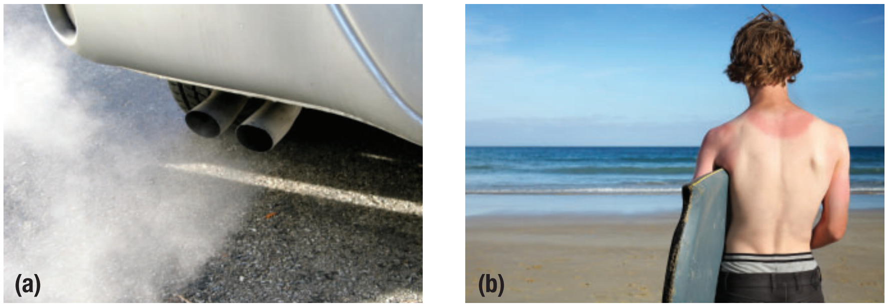


Figure 3 (a) Chemical (exhaust fumes) and (b) radiation (UV rays) mutagens can damage a cell's DNA.

Other chemical mutagens cause mutations by mimicking a DNA nucleotide. For example, individual nucleotides that have bonded with benzene molecules can be added to a replicating DNA strand. This chemical change can alter the shape of the DNA and negatively affect replication. Another example is ethidium bromide, which is used widely in biotechnology research and is similar in structure to a nitrogenous base. It can insert itself between the strands of the double helix and alter the structure of the molecule (**Figure 4**). This may lead to inaccuracies in replication and damage future generations of cells.

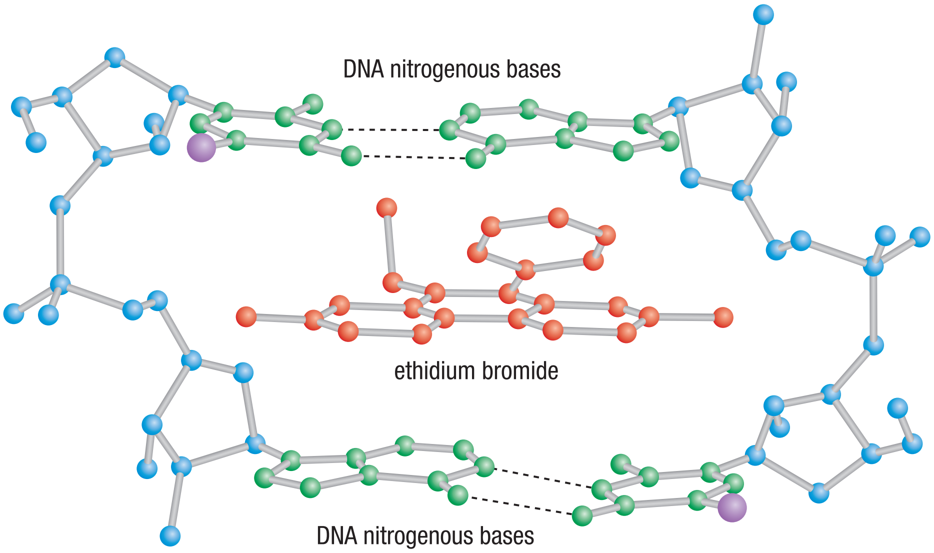


Figure 4 The structure of ethidium bromide is similar to the structure of a nitrogenous base. As a result, it has the ability to insert itself into a DNA molecule.

Radiation

Electromagnetic radiation can also cause mutations. Lower energy radiation, such as ultraviolet B radiation, can cause bonds to form between adjacent nucelotides along a DNA strand (a phenomenon known as non-homologous end joining). The bonds form a kink in the backbone of the DNA strand and complicate replication and transcription. This form of radiation-induced mutation can lead to certain types of skin cancer.

Higher-energy radiation, known as ionizing radiation, can strip molecules of electrons and break bonds within the DNA molecule, causing the rearrangement or deletion of large portions of chromosomes. Prolonged exposure to X-rays has been linked to the development of certain types of tumours. (This is why you wear a lead vest when getting dental X-rays.) Some of the highest-energy radiation comes from gamma rays and radioactive decay products of nuclear material. Children of residents near the former nuclear reactor at Chernobyl have suffered from various birth defects, and the 2011 tsunami-induced nuclear meltdowns in Japan have raised ongoing public health concerns. WEB LINK

Research This

Can Mutations Lead to a Longer Life?

Skills: Researching, Analyzing, Communicating SKILLS HANDBOOK A4.1

An organism that researchers frequently use to study lifespan is *Caenorhabditis elegans*, a microscopic roundworm that usually lives for two to three weeks. Researchers have discovered that *C. elegans* with a specific single-gene mutation called *daf-2* live twice as long as those that lack the mutation. This suggests that a single gene could dramatically regulate an organism's lifespan.

1. Using reputable sources, research *Caenorhabditis elegans*. Use your findings to answer the following questions.

A. Why is *C. elegans* an ideal organism to use for studying aging? T/I

B. How does the *daf-2* gene work, and how does this lead to life extension? T/I

C. What types of genes does the *daf-2* gene control when it is turned on? What types of genes does it control when it is turned off? K/U T/I

D. Describe an example of a different advantageous mutation in an organism. T/I A

E. Other examples of positive mutations are nylonase in bacteria and HIV immunity in people of European descent. Research how nylonase can be used to treat wastewater or how a mutation in the CCR5-delta 32 gene blocks the entry of the HIV virus. Present your findings in a written or electronic format of your choice. C A

WEB LINK

Mutations: Positive or Negative?

Despite the damaging effects of mutations, it is important to remember that mutations are ultimately responsible for the variety of individuals and species of organisms. A mutation that is truly harmful is only harmful to the individual. It does not cause immediate harm to the group or the species. A negative mutation renders the individual less fit than other members of its group and will be selected against by nature.

A beneficial mutation, however, is advantageous to the individual. The individual experiences greater survival and reproductive success, and passes the beneficial mutation on to future generations. The majority of mutations, however, are neutral. For example, silent mutations have no effect on an organism. Also, because most of our DNA (90 %) is non-coding, changes in the non-coding regions are almost always neutral and unnoticed. This is more likely to be true in eukaryotes, which usually have a lot of non-coding DNA, and less likely to be true in prokaryotes. Prokaryote DNA is mostly coding sequences, so a mutation is much more likely to be harmful than neutral or positive.

A mutation is only beneficial or negative in a given time and situation. What may seem like a negative trait may become useful under different circumstances. For example, the mutation that causes lactose tolerance in humans had no useful benefit until we began to domesticate large mammals and drink their milk. The mutation that causes sickle-cell anemia—a potentially lethal blood disease—also gives a heightened resistance to malaria.

Recently, researchers have discovered that a mutation in the gene filaggrin increases the risk of having a peanut allergy. In fact, one in five peanut allergy sufferers possesses the mutation. In our current environment, we view the peanut allergy as a disadvantage. However, the key point is not to consider mutations as inherently good or bad, but simply as a change that can lead to the evolution of life.

Investigation 7.5.1

Mutations: Cause for Concern? (p. 355)

Point mutations can have numerous effects on the sequences of amino acids that are produced. In this investigation, you will examine how single point mutations change the resulting amino acid sequence coded for by a given gene.

7.5 Review

Summary

- A mutation is a change in the sequence of DNA. A point mutation is specific to one base pair. Substitution involves the replacement of one base pair with another base pair. Other mutations involve the insertion or deletion of a nucleotide or the inversion of two adjoining base pairs.
- A small-scale mutation can be a silent mutation (which has no effect on the resulting amino acid sequence), a missense mutation (which changes a single amino acid in the sequence), a nonsense mutation (which results in a misplaced stop codon and prematurely ends translation), or a frameshift mutation (which causes the reading frame to shift in one direction or the other).
- Large-scale mutations include translocations (the movement of entire sequences of genes between chromosomes) and inversions (the reversal in the orientation of a gene in a chromosome.)
- Mutations can either arise spontaneously or be induced by mutagens. Mutagens include radiation and certain chemicals.
- Mutations have given rise to the diversity of life and are determined to be beneficial or harmful by natural selection.

Questions

1. Define the following terms:
   (a) mutation
   (b) frameshift mutation
   (c) point mutation
   (d) nonsense mutation
   (e) missense mutation K/U
2. The normal form of a gene contains the nucleotide sequence 3′-ATACCCGCCTTTTCGTACTTCCTAG-5′. What type of mutation is each of the following, and what effect will this mutation have on the structure of the protein encoded in the gene? K/U
   (a) Three extra adenine nitrogenous base pairs are inserted in positions 10, 11, and 12.
   (b) The third nucleotide is changed from an adenine to a thymine nucleotide.
   (c) The thymine nucleotide in position 10 is removed.
3. What is a duplication, and what evolutionary significance might it have? K/U A
4. Which of the following amino acid changes can result from a single base-pair substitution? Explain your reasoning. K/U
   (a) Phe→Leu
   (b) Ile→Thr
   (c) Ser→Arg
   (d) Asp→Gly
5. During the translation of a molecule of mRNA, the process is stopped prematurely. What type of mutation has occurred? What type of codon has been read by the ribosome? K/U
6. How can a mutation that is deemed negative to an individual when it first arises later become beneficial to individuals and the species as a whole? T/I
7. How does the information in this section relate to what you learned about cancer in Section 7.4? A
8. Which types of mutations might be neutral in their effect on an organism? A
9. Huntington's disease is a result of a trinucleotide repeat expansion. Using the Internet or other sources, research answers to the following questions. T/I
   (a) What is the trinucleotide repeat sequence in Huntington's?
   (b) How many repeats are required for the probable onset of Huntington's?
   (c) Why do the repeats cause Huntington's?
10. Smokers with the susceptibility locus on chromosome 15 increase their chance of developing lung cancer by 30 to 80 %. Using the Internet or other sources, research answers to the following questions. T/I
    (a) What is a susceptibility locus?
    (b) Should we be given the option of being tested for the presence of known susceptibility loci? Why or why not?
    (c) Does the lack of a susceptibility locus justify a person's decision to engage in health-damaging behaviour such as smoking? Why or why not?

WEB LINK

7.6 Genomes and Gene Organization

Earth is home to millions of diverse species (**Figure 1**). A zebra is white with black stripes. The sweat glands of a cow are in its nose. Bees can see ultraviolet light. Bee-pollinated flowers look different in UV light than they do in the human visual spectrum. From ants and sea stars to hummingbirds and humpback whales, from ferns and moss to pine trees and potatoes, from bacteria and blue-green algae to kelp—all these different species are the result of changes in sequence, length, and organization of a molecule that is composed of four nitrogenous bases. The genetic material of each and every species has the same organizational structure.

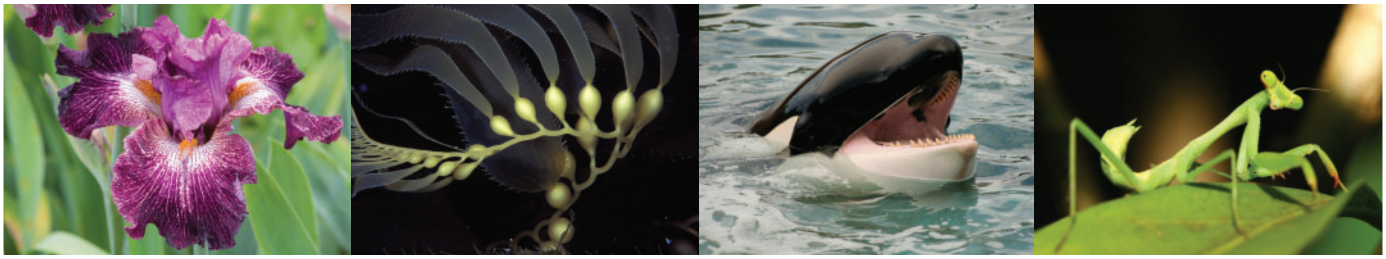


Figure 1 Earth is home to millions of diverse species of plants, animals, and other organisms.

Human DNA is found in the nucleus of human cells in duplicate. Each human nucleus contains two copies of the 22 autosomal chromosomes and one pair of sex chromosomes (XX or XY). Each autosomal chromosome is numbered by size from 1 to 22, with 1 being the largest. Each gene has two copies, known as alleles, that may be identical or different. Each allele of a given gene resides at the same locus on both homologous chromosomes. Each long strand of DNA is wrapped around proteins, which allow the chromosomes to pack tightly into the cell nucleus.

Human Genome Project the joint government and private sector research project that sequenced the human genome

In 1990, an ambitious project called the **Human Genome Project** was undertaken to determine the sequence of the 3 billion base pairs that make up the human genome. Over 200 scientists from around the world collaborated to sequence the genetic code. Knowing the sequence of the nitrogenous bases for humans, as they are ordered on each chromosome, is a monumental achievement in genetics. Even so, the size of a genome or the total number of genes in the genome reveals little about an organism's complexity. Scientists are now working toward a comprehensive understanding of the patterns in our genome organization and the way that these patterns produce the proteins required for human life.

Genome Components

Genome organization refers to the sequential organization of the genome. Eukaryotic genomes are composed of coding and non-coding regions. In humans, all the protein-coding sequences occupy less than 2 % of the genome and are functional as they code for proteins. Introns are non-coding regions in genes and occupy another 24 % of the genome (Section 7.2). The rest of the DNA, almost 75 % of the genome, occupies the spaces between the genes. Some of this intergenic DNA is functional and includes regulatory sequences, such as promoters. However, much of it, more than 50 % of the total genome, consists of repeated sequences that are non-functional.

variable number tandem repeats (VNTRs) non-coding, repeating sequences of DNA that vary in length between homologous chromosomes and between individuals

In eukaryotes, non-coding regions are filled with **variable number tandem repeats (VNTRs)**, also known as microsatellites. VNTRs are sequences of base pairs that repeat over and over again (for example, TAGTAGTAGTAG). The lengths of VNTRs vary, as do their positions in the genome. The number of these non-coding regions in an organism's genome is proportional to the complexity of the organism. Long repetitive non-coding DNA sequences are used as a defence mechanism against the shortfalls of DNA replication. Telomeres are non-coding regions at the ends of chromosomes that preserve coding DNA from being lost during replication (Section 6.6). Repetitive DNA sequences are also found near the centromeres and play a role during cell division. Two more types of repetitive DNA sequences are found in the genome: **LINEs (long interspersed nuclear elements)** and **SINEs (short interspersed nuclear elements)**. LINE-repetitive DNA is, on average, 6500 bp in length, whereas SINE-repetitive DNA is less than 500 bp in length. The origin and function of LINEs and SINEs are not yet clear.

A significant portion of the genomes of many, if not all, species is made up of DNA that originated from ancient viral infections. When certain viruses infect cells, they insert copies of their genetic code at random into the host cell genome. Often this inserted DNA is not active and behaves as simple non-coding sequences. If these insertions are passed on from generation to generation, they have the potential to spread and become part of the shared genome of entire species.

Eukaryotic genomes also contain transposons. **Transposons** are small sequences of DNA that can move about the genome and insert themselves into different chromosomes. A **pseudogene** has a nucleotide sequence that is similar to an existing gene but differs in certain base pairs, which make it unable to code for proteins. Pseudogenes are thought to be mutated versions of older genes, in other words, vestigial genes that have lost their evolutionary adaptive value. Pseudogenes remain in the genome but serve no function. Dolphins possess hundreds of pseudogenes that are mutated versions of genes originally associated with the sense of smell. Like most mammals, dolphin ancestors lived on land and had a keen sense of smell. As dolphins adapted to a life in the oceans, their sense of smell in air was of little or no value. As a result, mutations accumulated in these redundant genes, making them pseudogenes.

The quantity and particular sequence of both coding and non-coding regions are responsible for the diversity among organisms. For example, the mammalian genome is about 300 times the size of the yeast genome. However, the actual number of genes in each organism differs by only a factor of four. From this, it is evident that the complexity of a species does not depend on the total number of base pairs or genes within a given genome (its size) but on the organization of the genes and how they are regulated (its content).

LINEs (long interspersed nuclear elements) repetitive DNA sequences, approximately 6500 bp in length on average, interspersed throughout the genome

SINEs (short interspersed nuclear elements) repetitive DNA sequences, approximately 500 bp in length on average, interspersed throughout the genome

transposon a small segment of DNA that can move to a different position in the genome

pseudogene a sequence of DNA that is similar to an existing gene but does not code for proteins

Biodiversity and Genomes

With the human genome sequenced, scientists have begun to compare it with the genomes of other species to determine the molecular basis of differences in anatomy, physiology, and developmental patterns between species. Ultimately, species comparisons may reveal the mutational changes that have driven the evolution of our species and many others. This area of genomics is known as **comparative genomics**.

Comparative genomics has provided us with some surprising results. For example, 70 % of sea urchin genes have a human gene counterpart, whereas only 40 % of fruit fly genes do. The section of the sea urchin's genome that codes for its immune system is more complex than the immune system section of the human genome. Because the sea urchin can live up to 100 years, its immune system could shed some light on our understanding of the evolution of the human immune system.

Comparative genomics also includes the study of individual sequences of DNA. The differences in genes and gene fragments in different species can be analyzed to understand how cell functions vary from one organism to another. The advances in genomic science have strengthened our understanding of biodiversity and provided us with an increasingly complete description of the interconnections between different forms of life on Earth. However, genomic research has also challenged society to question the choices that are made in terms of the direction that research should take. CAREER LINK

comparative genomics the study of the organization, functions, and relationships of the genomes of different species

Reading Your Own Genome: Possibility or Probability?

The development of more efficient sampling, sequencing, and data storage technologies has led to the discovery of new genes and genetic information. We are already able to test for specific genes in our genomes to determine our susceptibility to various diseases, and we are fast approaching the benchmark of paying to have our genome sequenced.

It is highly probable that we will all be able to read our own genome and learn the fate of our health in the near future. Society will need to consider the consequences of this acquired knowledge. The improvement of scientific literacy among the public is vital for society to gain the most from these growing technologies and be able to make informed and wise decisions.

Research This

Should Life Be Barcoded?

Skills: Researching, Analyzing, Evaluating, Communicating, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK **A4.1**

DNA barcoding uses short fragments of mitochondrial genes to identify individual species (**Figure 2**). Some researchers argue that barcoding could provide a wealth of information and a tool for research. Others worry about the potential abuses of this technology.

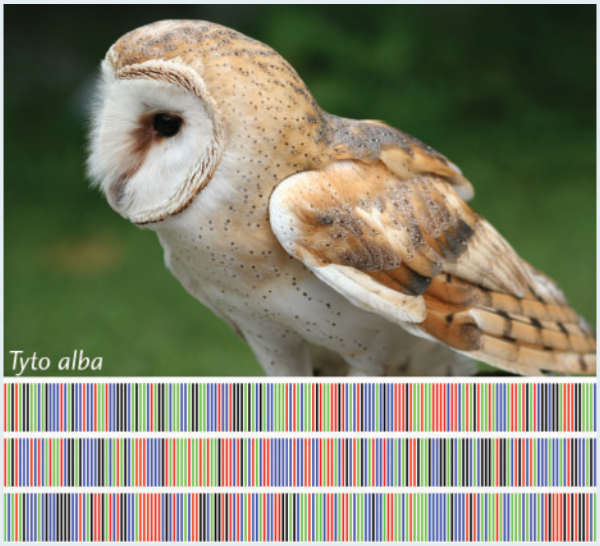


Figure 2 Mitochondrial DNA can be used to create a barcode that is unique to each species.

1. Using reputable sources, research the status of the Barcode of Life Project.

A. Where was the Barcode of Life Project started? T/I

B. What purpose does the Barcode of Life Project serve, and how does having a Barcode of Life database help in taxonomic research? T/I

C. Why would government agencies find a Barcode of Life helpful (for example, for consumer affairs issues)? T/I

D. How would a Barcode of Life benefit conservation organizations? T/I

E. Describe three non-related situations in which Barcode of Life data would be helpful. A

F. You are part of a government committee that has been asked to allocate funding to researchers, listed below, who are involved in different aspects of the Barcode of Life Project. A total of $1 million will be distributed. How would you distribute the funds among the following groups, and why? C A

- conservationists who want to measure the number of endangered species of lemur in Madagascar
- government scientists who want to develop a program in which all fish imports are checked for integrity (for example, that haddock is haddock and not cod)
- research scientists who want to develop and clarify further phylogenic trees for species of plants found in Indonesia
- a private scientific company that wants to patent the organism barcodes it produces, so that other groups cannot use them without paying a royalty

G. Based on your findings, write a report. Use an electronic or written format for your report, as instructed by your teacher. Make sure that you include a bibliography with your report. C

WEB LINK

7.6 Review

Summary

- Genome organization refers to the sequential structure of a genome.
- The human genome is composed of coding and non-coding regions. Only 2 % of the genome codes for proteins. The remaining genome is composed of introns within genes and repeating sequences between genes.
- The eukaryote genome contains transposons (transposable elements of DNA) and pseudogenes (non-coding sequences, similar to existing genes).
- The discipline of comparative genomics seeks to understand the genetic relationship between all forms of life on Earth.
- The declining cost and increasing efficiency of genomic technologies raises numerous ethical questions about the use of genomic information.

Questions

1. A large portion of the human genome consists of non-coding introns. Hypothesize some reasons that may explain this. K/U T/I
2. Using what you have learned about genes and genomes, what may be some of the functions of transposons? K/U T/I
3. What is a pseudogene, and how might a pseudogene arise within a genome? K/U T/I
4. The discipline of epigenetics seeks to understand the roles that introns and other non-coding sequences play in gene expression. Using the Internet and other electronic sources, research the field of epigenetics and determine the role that non-coding sequences may play in gene expression. C A
5. The genome of the tobacco plant (*Nicotiana tabacum*) contains 48 chromosomes. The human genome contains 46 chromosomes. Upon inspection, the tobacco plant appears to be less complicated than a human. Provide a reason why 46 chromosomes may result in more complexity than 48 chromosomes. T/I
6. In a flow chart, illustrate the organization of genetic material within a eukaryotic genome. K/U C
7. Describe the ramifications if a mutation were found in each of the following: K/U
   (a) intron
   (b) exon
   (c) telomeric region
   (d) SINE
   (e) pseudogene
   (f) variable number tandem repeats
8. Many people believe that the size of a genome is directly related to the complexity of the organism. Is this statement consistent with our present knowledge of DNA? K/U
9. Some of our human DNA consists of viral DNA that entered genomes hundreds of millions of years ago. Using the Internet and other sources, research viral DNA in the human genome. In paragraph form, explain whether you think this is advantageous. T/I

WEB LINK

7.7 Viruses: A Special Case

Vaccines for the seasonal flu have been around for many years. The Government of Ontario invests approximately $40 million each year to develop, promote, and administer the flu shot and ensure the health of Ontarians. Why is the flu so dangerous, and what causes it? Most healthy adults who contract the flu only experience mild symptoms, yet respiratory viruses can be a serious threat to children and the elderly. The flu is caused by the influenza virus (**Figure 1**). Each year, the flu is caused by a different strain of the virus, so a different vaccine must be developed. Some strains are more virulent (infectious) than others, and some affect people worldwide (pandemics).

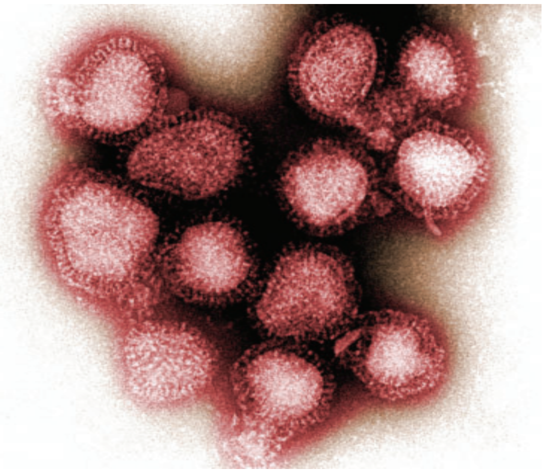
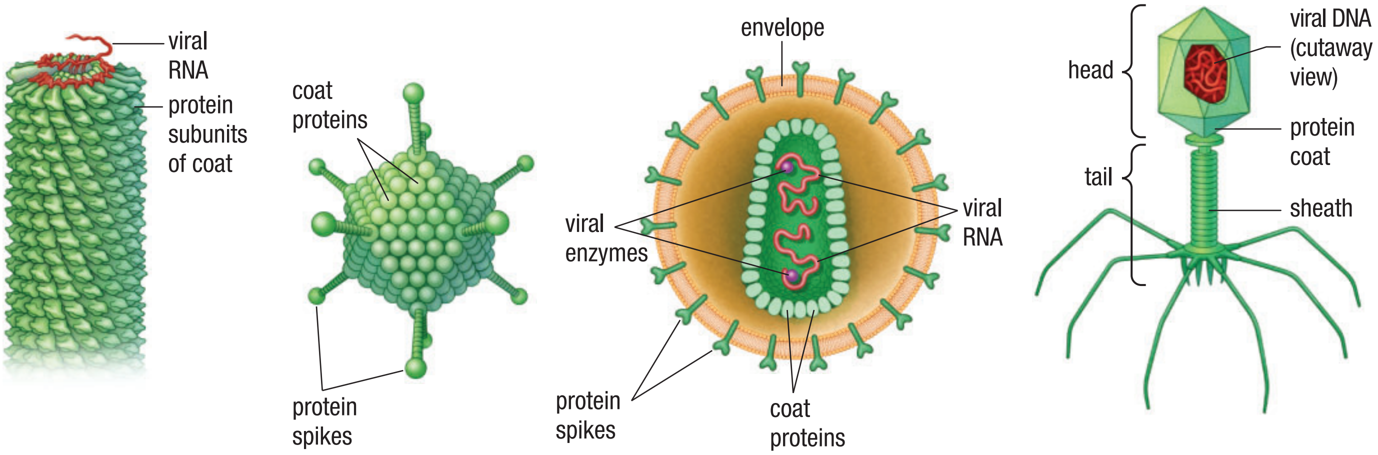


Figure 1 The influenza virus magnified

Viruses are not technically considered to be alive, due to their inability to replicate on their own as other living organisms do. However, because they *can* replicate themselves, they are classified in the same way as living organisms. As you learned in Grade 11 Biology, a virus is simply one or more nucleic acid molecules surrounded by a protein coat, called a capsid (**Figure 2**). In addition to the capsid, some viruses are surrounded by an envelope. The envelope is created when a virus leaves a host cell and part of the host cell membrane wraps around the virus.



(a) helical virus (tobacco mosaic virus)

(b) polyhedral virus (adenovirus)

(c) enveloped virus (HIV)

(d) complex polyhedral virus (bacteriophage)

Figure 2 (a) and (b) Viruses contain RNA or DNA as their genetic material, which is surrounded by a capsid. The capsid can take various shapes. (c) Some viruses are surrounded by an envelope. (d) Bacteriophages are viruses that infect bacteria.

Over 4000 species of viruses have been classified, and they vary widely in their size, genomic structure (RNA or DNA), the way that they replicate their genome, and their preferred host (**Table 1**).

Table 1 The Major Animal Viruses

Viral family	Envelope	Nucleic acid	Diseases
Adenoviridae	no	ds DNA	respiratory infections and tumours
Flaviviridae	yes	ss DNA	yellow fever, dengue, and hepatitis C
Hepadnaviridae	yes	ds DNA	hepatitis B
Herpesviridae	yes	ds DNA	oral herpes, genital herpes, cold sores, and mononucleosis
Poxviridae	yes	ds DNA	smallpox and cowpox

ds = double-stranded; ss = single-stranded

The genome of the influenza A virus contains only 8 genes, which code for 11 proteins. The virus's polymerase enzymes show a very high rate of replication error. This accounts for the large number of mutations that occur, and therefore the large number of strains. As a result, the virus changes from one flu season to the next.

Usually, a virus infects only a single species or a few closely related species. A virus may even infect only one organ system or a single tissue or cell type in its host. Of the roughly 80 viral families described to date, 21 include viruses that cause human diseases. Viruses also cause diseases in wild and domestic animals. Plant viruses cause annual losses of millions of tonnes of crops, especially cereals, potatoes, sugar beets, and sugar cane.

Replicating the Viral Genome Using Reverse Transcriptase

If a virus's genome is composed of DNA, transcription and translation occur in the ways that we have explored thus far. However, if single-stranded RNA acts as the hereditary molecule, the viral genome is replicated in a different manner.

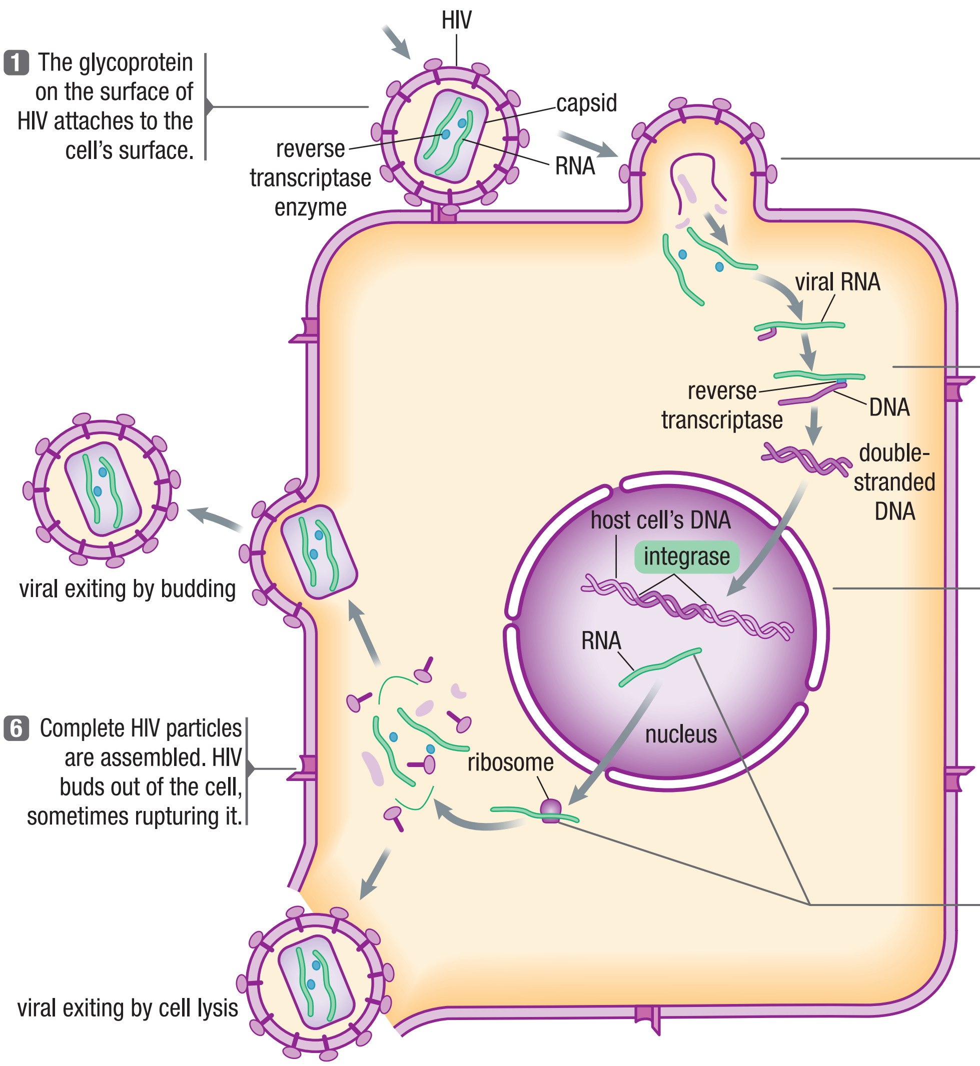
The RNA in the genome of a virus may code for an enzyme called **reverse transcriptase**. The viruses that use this enzyme are called **retroviruses**. One of the most widely studied retroviruses is the human immunodeficiency virus (HIV), which has killed about 25 million people worldwide. When a retrovirus infects a host cell, it injects its RNA genome along with the reverse transcriptase. Using the cell's supply of materials, the reverse transcriptase copies the viral RNA to make a complementary molecule of single-stranded DNA (**Figure 3**, next page). Then the reverse transcriptase directs the synthesis of a second DNA strand that is complementary to the first strand. The enzyme integrase, which is introduced to the host cell along with the RNA, incorporates the reverse-transcribed double-stranded DNA into the host cell genome. Transcription of the viral DNA results in the production of viral RNA. This RNA can serve as the genome for new viruses and can also be translated to produce viral proteins. The life cycle of an HIV retrovirus is shown in Figure 3. The manipulation of the host's own cellular machinery is what allows the virus to have such a simple structure and yet be so effective at infection.

reverse transcriptase a viral enzyme that uses RNA as a template strand to synthesize complementary DNA

retrovirus a virus that uses reverse transcriptase for replication

The Use of Viruses as Vectors

The ability of a virus to enter a cell and use the cell's replication enzymes provides scientists with a method for inserting new genetic material into an existing cell's genome. For example, the human gene for insulin has been inserted into the nucleus of safflower seeds. The resulting plants produce insulin in their cells, and the insulin can be extracted for therapeutic purposes.



1 The glycoprotein on the surface of HIV attaches to the cell's surface.

2 The viral contents enter the cell by endocytosis.

3 First, reverse transcriptase catalyzes the synthesis of a DNA copy of the viral RNA, and then it catalyzes the synthesis of a second DNA strand complementary to the first one.

4 The double-stranded DNA is then incorporated into the host cell's DNA by the action of the enzyme integrase.

5 Transcription of the DNA results in the production of RNA. This RNA can serve as the genome for new viruses and can be translated to produce viral proteins.

6 Complete HIV particles are assembled. HIV buds out of the cell, sometimes rupturing it.

Figure 3 Retroviruses use their host's own replication and translation enzymes to multiply.

transduction the use of viral vectors to introduce new genetic material into a cell

A viral vector is a virus that is used to transfer the DNA from a donor to a host. The process of inserting genetic material into a cell or bacterium using a viral vector is known as **transduction**. Researchers remove the harmful genetic material from the virus and replace it with the desired genetic material. Retroviruses, adenoviruses, and herpes viruses are widely used for transduction. The original viral genome and the new genetic material must be engineered so they do not damage the host cell. The modified virus must be highly stable to ensure the successful uptake of the new genes. You will learn about genetic engineering in Chapter 8. CAREER LINK

Transduction, as a method of research, has been used since the 1960s. It is now being developed for therapeutic purposes. The discipline of genetic therapy uses knowledge of the genetic causes of disease, along with transduction, to introduce genetic material into human cells, potentially repairing or even replacing defective genes. CAREER LINK WEB LINK

UNIT TASK **BOOKMARK**

Consider how you can apply your understanding of viruses as vectors as you select your topic for your Unit Task on page 410.

7.7 Review

Summary

- Viruses have small genomes that consist of only RNA or DNA. They rely on their host's genetic machinery to replicate themselves.
- Many errors are made by a virus's polymerase enzymes, especially those of the influenza A virus. As a result, there is a very high mutation rate.
- A retrovirus uses an enzyme called reverse transcriptase to transcribe its RNA genome into DNA. The viral DNA is then incorporated into the host's genome by an enzyme called integrase, then transcribed and translated to produce virus proteins and viral RNA. These proteins and RNA are used to assemble new virus particles.
- Viruses have many research and therapeutic applications. Transduction is the use of viral vectors to introduce new genetic material into an existing cell.

Questions

1. Why do we need a different flu vaccine every year? K/U
2. Describe the process that is used by retroviruses to replicate their genetic material. K/U
3. Using the Internet or other sources, research the use of transduction as a therapeutic procedure for humans. Identify some advantages and disadvantages of this type of research. Report your findings using a format approved by your teacher. 🌐 T/I C
4. Two viral classification systems exist: the Hierarchical Virus Classification System and the Baltimore Classification System. Using the Internet or other sources, research these two systems. Present your findings in table format. 🌐 T/I C
5. Usually, a virus infects only a single species or a few closely related species. Using the Internet and other sources, do research and discuss this statement. Use the influenza A virus or the HIV virus as an example. 🌐 T/I
6. Plant viruses cause annual losses of millions of tonnes of crops, especially cereals, potatoes, tomatoes, sugar beets, and sugar cane. Choose a plant virus and describe its structure, its method of infection, and its effects on the specific plant and any related plants. Use the Internet and other sources for your research. 🌐 T/I

🌐 WEB LINK

CHAPTER 7 Investigations

Investigation 7.3.1 ACTIVITY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Protein Synthesis

In this investigation, you will examine the genetic makeup of a fictitious organism called the vinki. The vinki has a single long chromosome with six genes, which determine fur length, ear size, eye colour, gender, nasal design, and means of locomotion. Like most organisms, not all vinkis are identical, and genetic variations lead to variations in traits or phenotypes.

In groups of six, you will study the DNA sequence of an individual vinki. Each group member will receive a DNA strand for one of the vinki's six genes. From this, you will determine the structure of the corresponding mRNA and the amino acid composition of the translated protein. Then, you will deduce the phenotype of your vinki based on the gene.

Purpose

To determine the phenotypic characteristics of a fictitious animal called the vinki by transcribing and translating six given DNA strands

Materials

- DNA strand
- glue
- 2 pieces of blank legal-sized paper
- scissors
- nucleotide templates for DNA, mRNA, tRNA, ribosome, and amino acids
- tape
- mRNA codon chart

Procedure

SKILLS HANDBOOK A2.5

1. Divide into groups of six, as instructed by your teacher.
2. Obtain the six DNA strands for a single vinki from your teacher. Divide the DNA strands among your group so that each person has the DNA for one of the six genes.
3. Glue your DNA strand to a piece of paper.
4. Using your knowledge of DNA replication, build a complementary DNA strand opposite the glued DNA strand.
5. Choose the DNA strand that will serve as a template strand. Remember that all nucleic acids, whether DNA or RNA, are made in the 5′ to 3′ direction.
6. Cut out all the mRNA nucleotides from one of the worksheets in your package. Pair the appropriate mRNA nucleotides with the DNA template strand.
7. Double-check your mRNA strand and tape the nucleotides together. Label the 5′ end and the 3′ end.
8. Cut out the ribosome from the worksheets, and cut slits at the A and P sites.
9. Cut out the tRNA molecules and the amino acids from the worksheets. Copy the anticodons on the tRNA molecules from the table provided by your teacher.
10. Charge all the tRNA molecules by taping a corresponding amino acid to each tRNA molecule.
11. Place the 5′ end of the mRNA strand on the A site of the ribosome. Thread the mRNA strand through the slit in the ribosome. When you reach the start codon, stop threading the mRNA. Make sure that the start codon is in the correct site of the ribosome to initiate translation.
12. Pair the start codon with the appropriate tRNA.
13. Move the mRNA along one position on the ribosome. Determine which tRNA to place in this position. Tape the two amino acids together, and remove the first amino acid from its tRNA. Recharge this tRNA with the appropriate amino acid for later use if required.
14. Pull the mRNA through the ribosome. Keep building the polypeptide chain until a stop codon is reached.
15. Record the amino acid sequence of this polypeptide chain.
16. Using **Table 1**, determine the trait of your vinki for your given gene.

Table 1 Sequence and Trait Chart

Amino acid sequence	Trait
Arg-Val-Asp	long fur
Lys-Glu-Gly	short fur
Thr-Cys-Lys	floppy ears
His-Gln-Arg	short ears
Ser-Ser-Ala	quadruped
Tyr-Cys-Phe	bipedal
Glu-Glu-Val	blue eyes
Glu-Val-Val	red eyes
His-Arg-Lys	nose with two nostrils
Ile-Tyr-Cys	nose with three nostrils
Ala-Ala-Leu	male
Phe-Ala-Gly	female

Analyze and Evaluate

(a) What trait did the gene code for? T/I

(b) What six traits does your vinki have? Sketch your vinki. T/I C

(c) Why is it important that the correct DNA strand be used as the template strand? What might have happened to your polypeptide if you had not used the template strand to build the complementary mRNA? T/I

(d) Where in the cell does Step 4 take place? Step 6? Step 13? K/U

Apply and Extend

(e) What would have happened to the traits of your vinki if a nucleotide substitution had occurred? Support your answer by giving a specific example, based on the information in Table 1. T/I

(f) How would the wobble hypothesis apply to this scenario and to your synthesis of the vinki's protein? T/I

(g) Using your knowledge of translation and transcription, what modifications would you make to improve the accuracy of this simulation? K/U T/I

Investigation 7.5.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Mutations: Cause for Concern?

Several types of mutations can affect an organism's genes. The extent of the effects varies widely, from no difference to the production of a dysfunctional protein or no protein at all.

Purpose

To demonstrate how gene mutations affect the production of proteins

Equipment and Materials

- DNA template strand (bacterial DNA)
- copy of the genetic code

Procedure

SKILLS HANDBOOK A2.4

1. Your teacher will assign you a DNA template strand. Draw a data table similar to **Table 1** in your notebook and record the base sequence of the template strand.

Table 1

Step	Base sequence
Original DNA template strand	
mRNA from Step 2	
protein from Step 3	
protein from Step 4(a)	
protein from Step 4(b)	
protein from Step 4(c)	
protein from Step 4(d)	

2. Write the base sequence for an mRNA strand that would be transcribed from the template strand. Record the base sequence of this mRNA strand.
3. Translate your mRNA. Record the sequence of amino acids in your polypeptide chain.
4. Perform each of the following changes to your original sequence. Transcribe the new sequence and translate it. Record the resulting amino acid sequence. Always begin with the original sequence.
   (a) Replace the 3rd T by a G.
   (b) Delete the 7th base.
   (c) Insert an A between the 11th and 12th bases.
   (d) Delete the 8th, 9th, and 10th bases.

Analyze and Evaluate

(a) For each change you made in Step 4, identify the type of mutation that occurred and the effect of the mutation on the final polypeptide chain. T/I

Apply and Extend

(b) What would happen if a nucleotide were deleted in each of the following regions of a gene? T/I
   (i) the promoter region
   (ii) an exon
   (iii) an intron

(c) Research a genetic disorder that is caused by a substitution, addition, or deletion mutation. Find out what gene is involved and how the protein is altered as a result. Describe the effect of the disorder on an individual's health and lifestyle. Consider the cost of treatment. Report your findings in paragraph form. T/I C

WEB LINK

CHAPTER 7 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 310. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 310. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

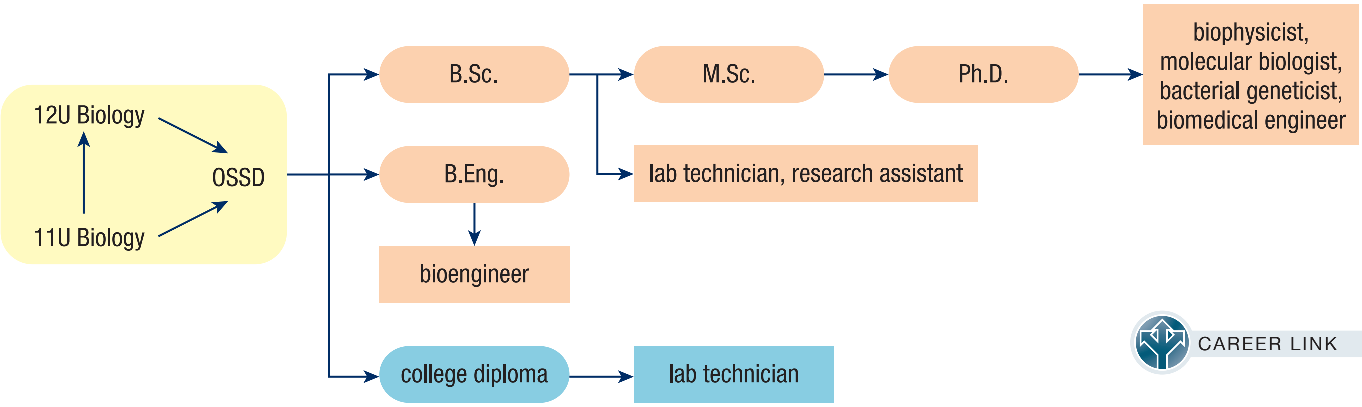
- one gene–one enzyme hypothesis (p. 313)
- one gene–one polypeptide hypothesis (p. 313)
- central dogma (p. 313)
- transcription (p. 313)
- translation (p. 313)
- messenger RNA (mRNA) (p. 315)
- transfer RNA (tRNA) (p. 315)
- ribosomal RNA (rRNA) (p. 315)
- RNA polymerase (p. 315)
- template strand (p. 315)
- precursor mRNA (pre-mRNA) (p. 316)
- genetic code (p. 316)
- codon (p. 317)
- start codon (initiator codon) (p. 317)
- stop codon (p. 317)
- promoter (p. 319)
- TATA box (p. 319)
- coding strand (p. 319)
- termination sequence (p. 320)
- poly(A) tail (p. 321)
- 5′ cap (p. 321)
- exon (p. 322)
- intron (p. 322)
- spliceosome a (p. 322)
- small ribonucleoprotein (snRNP) (p. 322)
- alternative splicing (p. 322)
- anticodon (p. 325)
- aminoacylation (p. 326)
- aminoacyl–tRNA (p. 326)
- reading frame (p. 327)
- polysome (p. 329)
- insulin (p. 332)
- *lac* operon (p. 332)
- operator (p. 332)
- repressor protein (p. 332)
- inducer (p. 333)
- corepressor (p. 334)
- point mutation (p. 340)
- substitution (p. 340)
- insertion (p. 340)
- deletion (p. 340)
- inversion (p. 340)
- single nucleotide polymorphism (SNP) (p. 340)
- missense mutation (pp. 340–341)
- nonsense mutation (pp. 340–341)
- silent mutation (pp. 340–341)
- frameshift mutation (pp. 340–341)
- translocation (p. 342)
- spontaneous mutation (p. 342)
- induced mutation (p. 342)
- mutagen (p. 342)
- Human Genome Project (p. 346)
- variable number tandem repeats (VNTRs) (p. 346)
- LINEs (long interspersed nuclear elements) (p. 347)
- SINEs (short interspersed nuclear elements) (p. 347)
- transposon (p. 347)
- pseudogene (p. 347)
- comparative genomics (p. 347)
- reverse transcriptase (p. 351)
- retrovirus (p. 351)
- transduction (p. 352)

CAREER PATHWAYS

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

SKILLS HANDBOOK A6

1. Select two careers related to genetics and protein synthesis that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What are the required educational programs? Prepare a brief report of your findings.


12U Biology
11U Biology
OSSD
B.Sc.
M.Sc.
Ph.D.
biophysicist, molecular biologist, bacterial geneticist, biomedical engineer
lab technician, research assistant
B.Eng.
bioengineer
college diploma
lab technician

CAREER LINK

CHAPTER 7 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What is the name of Beadle and Tatum’s original hypothesis? (7.1) K/U
   - (a) one gene–one sequence hypothesis
   - (b) one gene–one enzyme hypothesis
   - (c) one gene–one peptide hypothesis
   - (d) one gene–one polypeptide hypothesis
2. What is the sequence of information transfer, as outlined by the central dogma? (7.1) K/U
   - (a) DNA → tRNA → mRNA → polypeptide
   - (b) DNA → mRNA → tRNA → polypeptide
   - (c) DNA → mRNA → rRNA → polypeptide
   - (d) DNA → rRNA → tRNA → polypeptide
3. Where is the TATA box found? (7.2) K/U
   - (a) in the termination sequence that stops DNA polymerase
   - (b) in the termination sequence that stops RNA polymerase
   - (c) in the promoter that enables the binding of DNA polymerase
   - (d) in the promoter that enables the binding of RNA polymerase
4. What happens during capping and tailing? (7.2) K/U
   - (a) A methyl 5′ tail and a poly(A) cap are added.
   - (b) A methyl 3′ tail and a poly(A) cap are added.
   - (c) A methyl 5′ cap and a poly(A) tail are added.
   - (d) A methyl 3′ cap and a poly(A) tail are added.
5. How is tRNA different from mRNA? (7.3) K/U
   - (a) It binds 5′→3′.
   - (b) It is generally smaller.
   - (c) It forms a cloverleaf shape.
   - (d) all of the above
6. Which anticodon pairs with the DNA sequence 5′-ACA-3′? (7.3) K/U
   - (a) 3′-UGU-5′
   - (b) 3′-ACA-5′
   - (c) 5′-UGU-3′
   - (d) 5′-ACA-3′
7. How is the *lac* operon inhibited? (7.4) K/U
   - (a) The *lac* repressor is not synthesized by the *lacI* gene.
   - (b) RNA polymerase is inhibited by high concentrations of allolactose.
   - (c) The *lac* repressor is inhibited by high concentrations of allolactose.
   - (d) Allolactose is not present to bind with the *lac* repressor.
8. Which term refers to a point mutation that results in a different amino acid in a particular position? (7.5) K/U
   - (a) missense mutation
   - (b) silent mutation
   - (c) nonsense mutation
   - (d) frameshift mutation
9. Which statement about variable number tandem repeats is correct? (7.6) K/U
   - (a) They vary proportionally with the complexity of the organism.
   - (b) They are thought to help prevent DNA replication problems.
   - (c) They are non-coding regions.
   - (d) all of the above
10. How are viruses classified? (7.7) K/U
    - (a) by genomic structure
    - (b) by preferred host
    - (c) by shape
    - (d) all of the above

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Translation is the process of producing a gene from a protein. (7.1) K/U
12. Translation occurs in the cytosol of both prokaryotes and eukaryotes. (7.1) K/U
13. Exons are transcribed to build pre-mRNA in eukaryotes. (7.2) K/U
14. Prokaryotes use different types of RNA polymerase to transcribe coding and non-coding genes. (7.2) K/U
15. The wobble hypothesis proposes that the 61 sense codons require 61 distinct tRNA molecules. (7.3) K/U
16. The hydrolysis of GTP provides the energy for polypeptide chain elongation. (7.3) K/U
17. Most of the human genome is composed of LINEs, SINEs, and pseudogenes. (7.6) K/U
18. Mutations always lead to harmful effects. (7.5) K/U
19. Transposons can move around the genome with no effect. (7.6) K/U
20. Reverse transcriptase allows a virus to insert its RNA into its host’s DNA. (7.7) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 7 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. What is AUG? (7.1) K/U
   (a) a codon that specifies methionine
   (b) the first coding triplet in eukaryotic mRNA
   (c) the first coding triplet in prokaryotic mRNA
   (d) all of the above
2. Which DNA sequences do the tRNA anticodon sequences CUA, UGU, and AAA correspond to? (7.1) K/U
   (a) CTA, TGT, and AAA
   (b) CUA, UGU, and AAA
   (c) GAT, ACA, and TTT
   (d) GAU, ACA, and UUU
3. Which of the following describes how mRNA is formed? (7.1) K/U
   (a) 3′ to 5′ direction and antiparallel to the DNA
   (b) 3′ to 5′ direction and complementary to the DNA
   (c) 5′ to 3′ direction and antiparallel to the DNA
   (d) 5′ to 3′ direction and complementary to the DNA
4. How is the central dogma best described? (7.1) K/U
   (a) an explanation of how genetic information flows
   (b) an explanation of how proteins are regulated by DNA
   (c) an explanation of the evolution of proteins
   (d) an attempt to explain how genes function
5. mRNA differs from pre-mRNA because of
   (a) the addition of a poly(A) tail
   (b) the addition of a 3′ cap
   (c) the removal of introns
   (d) all the above (7.2) K/U
6. Which is the correct sequence of transcription? (7.2) K/U
   (a) initiation → termination → modification
   (b) initiation → elongation → termination
   (c) promotion → elongation → termination
   (d) promotion → elongation → modification
7. In eukaryotic cells, where is the DNA transcribed into mRNA? (7.2) K/U
   (a) nucleus
   (b) cytosol
   (c) ribosome
   (d) mitochondrion
8. Which amino acid is carried by a tRNA molecule with the anticodon 3′-CUA-5′? (7.3) K/U
   (a) histidine
   (b) leucine
   (c) aspartic acid
   (d) glutamic acid
9. When does a polysome occur? (7.3) K/U
   (a) when an enzyme digests the poly(A) tail
   (b) when more than one ribosome translates an mRNA molecule
   (c) when more than one ribosome transcribes an mRNA molecule
   (d) when more than one mRNA is read by a ribosome at one time
10. What is one similarity between prokaryotes and eukaryotes in translation? (7.3) K/U
    (a) Elongation occurs at a rate of 15 to 20 elongation cycles per second.
    (b) During termination, the stop codon appears and a release factor binds so that the polypeptide is released.
    (c) mRNA is translated by ribosomes in the cytosol as it is being transcribed from DNA.
    (d) Some translation occurs in mitochondria and chloroplasts.
11. The addition of an acetyl group (CH_3COO^-) to the histones
    (a) loosens a histone complex, making the promoter accessible
    (b) results in the histones attaching themselves to the promoter to increase the rate of transcription
    (c) results in the upstream regulation of the protein being transcribed
    (d) provides a substrate that the RNA polymerase can bind to initiate transcription (7.4) K/U
12. What does upstream regulation mean? (7.4) K/U
    (a) RNA polymerase must read the operator prior to the promoter region.
    (b) RNA polymerase must read the promoter prior to the operator.
    (c) RNA polymerase must read the operator prior to the coding region.
    (d) RNA polymerase must read the coding region prior to the operator.
13. What causes the decrease in protein length that occurs in β-thalassemia? (7.5) K/U
    (a) frameshift mutation
    (b) missense mutation
    (c) nonsense mutation
    (d) silent mutation
14. Transposable elements provide proof that genetic information
    (a) can move between individuals
    (b) can move between species
    (c) can move within a genome
    (d) cannot move without causing mutations (7.5) K/U

15. What is studied in comparative genomics? (7.6) K/U
    (a) how to insert DNA into humans
    (b) how to turn on genes in humans
    (c) how genes differ between species
    (d) how humans can live longer using foreign DNA
16. Which feature of viruses makes them useful in medicine? (7.6) K/U
    (a) their simple genetic complement
    (b) their ability to enter another cell and use its machinery
    (c) their ability to be stored for a long period of time
    (d) their high mutation rate

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

17. Garrod concluded that alkaptonuria was an “inborn error of metabolism.” (7.1) K/U
18. During the formation of a polypeptide, tRNA is transcribed from the DNA, exits the nucleus, and is translated on a ribosome to mRNA molecules, which carry the amino acids to form the polypeptide. (7.1) K/U
19. RNA polymerase requires a primer when making a complementary strand. (7.1) K/U
20. tRNA binds with proteins to form ribosomes. (7.1) K/U
21. Prokaryotes use spliceosomes to remove exons during post-transcriptional modification. (7.2) K/U
22. The process of alternative splicing results in different combinations of exons being removed to synthesize multiple proteins from the one gene. (7.2) K/U
23. Protein synthesis occurs faster in prokaryotes because transcription and translation both occur in the cytosol. (7.3) K/U
24. DNA is transcribed to a complementary $3' \rightarrow 5'$ mRNA, and the mRNA is complementary to $5' \rightarrow 3'$ anticodons on tRNA. (7.3) K/U
25. The formation of proteins is faster in eukaryotes than in prokaryotes because polysomes can form in the nucleus, coupling transcription and translation. (7.3) K/U
26. Post-transcriptional control of genes can be accomplished using proteins that mask mRNA. (7.3) K/U
27. The *trp* repressor is inhibited by high concentrations of tryptophan. (7.4) K/U
28. When lactose is absent, the *lac* repressor is inactive and binds to the promoter. (7.4) K/U
29. Ionizing radiation is considered a mutagen because it has the ability to break bonds within the DNA molecule, causing the rearrangement or deletion of large portions of chromosomes. (7.5) K/U
30. Silent mutations insert, delete, or change base(s) in a gene and thereby usually alter the protein. (7.5) K/U
31. Transposons are mutated vestigial genes that have lost their evolutionary adaptive value. (7.6) K/U
32. In transduction, viral vectors are used to insert transgenic material into cells. (7.7) K/U

Match each term on the left with the most appropriate description on the right.

33. (a) mRNA
    (b) RNA polymerase
    (c) transcription
    (d) tRNA
    (e) translation
    (f) rRNA

    (i) transfer of information from DNA to mRNA
    (ii) structural component of a ribosome
    (iii) reads the DNA template strand and synthesizes precursor mRNA
    (iv) intermediary between DNA and ribosomes
    (v) transfer of information from mRNA into a polypeptide
    (vi) short single-stranded sequence of 70 to 90 ribonucleotides, which loops back on itself (7.1, 7.2, 7.3) K/U

34. (a) LINEs
    (b) transposon
    (c) SINEs
    (d) pseudogene
    (e) intron
    (f) exon

    (i) a non-coding sequence of DNA or RNA
    (ii) a sequence of DNA that is similar to an existing gene but does not code for proteins
    (iii) repetitive DNA sequences, approximately 6500 bp in length on average
    (iv) a small sequence of DNA that can move about the genome
    (v) a sequence of DNA or RNA that codes for part of a gene
    (vi) repetitive DNA sequences, approximately 500 bp in length on average (7.2, 7.6) K/U

Write a short answer to each question.

35. Write the amino acid sequence that corresponds to the DNA template strand 5′-GTTGATTTTCGC-3′. (7.1) K/U
36. Identify at least three different DNA sequences that correspond to the polypeptide sequence Gly-His-Ile. (7.1) K/U
37. Describe the process of alternative splicing. (7.2) K/U
38. Outline the importance of snRNPs in RNA splicing. (7.2) K/U
39. What is the purpose of the aminoacylation of tRNA? (7.3) K/U
40. List the advantages that prokaryotes have over eukaryotes in protein synthesis. (7.3) K/U
41. What are the effects of the poly(A) tail during translation in eukaryotes? (7.4) K/U
42. Why is it important that cells regulate genes? (7.4) K/U
43. Explain the role of the following three mRNA codons: UAA, UGA, and UAG. (7.5) K/U
44. List the different types of mutagens, and give an example of each. (7.5) K/U
45. How do scientists think the human genome benefits from transposons, LINEs, and SINEs? (7.6) K/U
46. List the genomic structures that are found in viruses. (7.7) K/U

Understanding

47. Suppose that you are given the following data from a sample of a nucleic acid. What can you conclude from the data? Why? (7.1) K/U T/I

    adenine: 25 %

    uracil: 30 %

    guanine: 40 %

    cytosine: 5 %
48. Explain how Garrod's work with alkaptonuria helped him understand the nature of a gene. (7.1) K/U
49. Use a Venn diagram to compare and contrast the codons and anticodons found in RNA. (7.1) K/U T/I C
50. Explain mathematically why the amino acid sequence Arg-Leu-Ser is a good example of the wobble hypothesis. (7.1) K/U T/I
51. Use a labelled diagram to illustrate the formation of mRNA from a double-stranded section of DNA. (7.2) K/U C
52. You are asked to research a gene that appears in both prokaryotes and eukaryotes. One of the genes is 70 kbp in length and the other is only 20 kbp. Which belongs to which group? Explain. (7.2) K/U T/I
53. Cryptography is the study of codes. What properties of RNA and transcription could you use to manufacture a genetically based secret code? (7.2) K/U T/I
54. Explain the significance of alternative splicing. (7.2) K/U T/I
55. Explain the differences between the A, E, and P sites of the ribosome. (7.3) K/U T/I
56. The antibiotic erythromycin works by blocking ribosomal movement (translocation) along an mRNA strand in some prokaryotes. Predict the effect on protein synthesis. (7.3) K/U T/I
57. Copy **Table 1** into your notebook. Use your knowledge of the genetic code, mRNA, tRNA, and amino acids to complete the table. Assume that the table is read from left to right. (7.1, 7.2, 7.3) T/I

Table 1

DNA template strand		G							
DNA other strand						A			
mRNA			U	U					
tRNA	C				U				
amino acids							Trp		

58. Draw the feedback mechanism that is involved in regulating the *lac* enzymes. (7.4) K/U T/I C
59. Explain the importance of ubiquitin in post-translational modification. (7.4) K/U T/I
60. Defend the statement: Not all mutations are harmful. (7.5) K/U T/I
61. Non-coding sequences used to be referred to as "junk" DNA. How has our understanding of non-coding sequences caused the name change? (7.5) K/U T/I
62. Use a graphic organizer to compare and contrast the *lac* and *trp* repressors. (7.6) K/U T/I C
63. Use a flow chart to summarize how a retrovirus enters a cell and hijacks the cell's replication machinery. (7.7) K/U T/I C

Analysis and Application

64. Suppose that you are investigating an organism that has attached itself to the outside of the International Space Station. (7.1) T/I
    (a) You discover that this organism uses six different nucleotides to code for 180 amino acids. Suggest the minimum number of nucleotides that might make up a single codon.
    (b) How would your answer to (a) change if you discovered that this organism actually uses six nucleotides to code for 356 amino acids? Provide a mathematical solution.

65. Compare and contrast DNA replication and mRNA transcription. (7.2) T/I

66. Eukaryotes can vary the number of proteins that are synthesized by an individual gene based on the number of introns in a sequence. Copy **Table 2** into your notebook and complete it to compare the effect of introns on the number of proteins using a sequence consisting of 5 exons. Assume that any combination can occur, but regions cannot be repeated. (7.2) K/U T/I

Table 2

Number of exons	Number of introns	Number of possible genes
5	1	5
5	2	
5	3	
5	4	

67. During an investigation of the promoter region of a gene, you apply heat to two sections of DNA that you believe could be promoter regions. One region unwinds at 80 °C and the other unwinds around 60 °C. Which of the two strands contains the promoter? Explain (7.2) K/U T/I

68. You are growing cells in culture and you briefly introduce fluorescently labelled uracil into the cell culture (treatment A). Then you wash out the fluorescently labelled uracil and reintroduce unlabelled uracil (treatment B). Where would you expect to find the fluorescence during treatments A and B? (7.2) K/U T/I

69. Tetracycline, a common medication that is used to treat bacterial infections, prevents the aminoacyl–tRNA from binding to the ribosomal subunit. Describe the effect on the cell. (7.3) T/I

70. The wobble hypothesis predicts that fewer than 61 tRNA molecules are required to read the 61 sense codons. State the minimum number required. Explain. (7.3) K/U T/I

71. The final steps in deciphering the genetic code involved using synthetic mRNA, with known mRNA sequences, as well as a complete set of tRNA. One by one, all but three of the tRNA sequences were matched to specific amino acids. (7.3) K/U T/I A
    (a) Which three tRNA sequences did not attract an amino acid?
    (b) What experiment could you perform to determine the function of these three codons?

72. Defend the following statement: The mechanisms of gene regulation in prokaryotes are profoundly different from those in eukaryotes. (7.4) K/U T/I

73. Examine the following sequences of DNA before and after treatment with a mutagen. Identify the type of mutation and describe the effect, if any, on the amino acid sequence.

    Before: 5′-CAC TCT TGC CDC-3′

    After: 5′-CAC TCT TGT CDC-3′ (7.5) K/U T/I

74. Use the DNA sequence 5′-ACA GGC TAA TGG-3′ to demonstrate an inversion mutation. How could this mutation change the polypeptide? (7.5) K/U T/I

75. Currently, Canada has no clear legislation on genetic rights. Take the role of a citizen, doctor, lawyer, geneticist, genetic counsellor, or drug manufacturer. Write a set of guidelines that you think the Government of Canada should adopt. (7.6) K/U C A

Evaluation

76. Consider the following statement: The genetic code is degenerate. (7.1) K/U T/I A
    (a) What does this statement mean?
    (b) Determine the ratio of sense codons that have synonyms to sense codons that do not.
    (c) Hypothesize how degeneracy could protect a cell from mutations.
    (d) Develop a testable question that would use degenerate DNA to examine your hypothesis in (c).

77. You have been investigating the production of a novel protein in a human cell. However, you cannot determine where the protein is being produced. You administer a drug called cyclohexamide, which is a eukaryotic protein transcription inhibitor. The protein is still produced. Where do you think it is being produced? Explain your answer. (7.2, 7.3) K/U T/I

78. As a grad student, you have been working on the gene to produce human insulin. During a set of routine tests on a gene that has been working to produce insulin, you attempt to use *E. coli* as a method of producing human insulin. However, despite your best attempts, the *E. coli* will not produce the protein. (7.3) K/U T/I A
    (a) Explain why the insulin is not being synthesised.
    (b) What would you have to do to get the process to work?

79. All the cells in an organism contain the same DNA. However, every cell does not transcribe or translate the same information, or even the same information in the same way. In a paragraph, explain how this illustrates the idea that you are the product of your environment. (7.4) K/U T/I

80. Copy **Figure 1** into your notebook. Indicate the position of the promoter region by drawing a rectangle and the position of the terminator region by drawing a square. Explain your choice of locations. (7.4) K/U T/I C

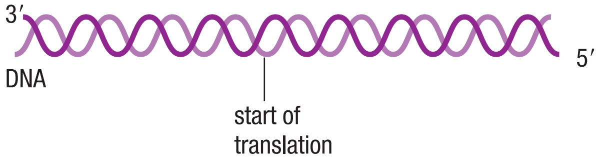


Figure 1

81. You have been asked by Health Canada to verify the claim that the drug Actinomycin D blocks transcription in bacteria. You decide to use a culture of *E. coli*. How would you determine if this claim is correct? (7.4) K/U T/I

82. Use the following sequences to answer the questions below. (7.3, 7.4) K/U T/I

Sequence A: 5′-GCAGGCCATATAAAATAGCGCCA
TACTAGATACGGGCCATATTATTGCATATCCGC
CGATTACAGGATTTAATTTGGGAATTCCCCGAT
TAACGCGATCGATCGGGCCATATCGATATGCAT
CGTAATCCGGTAGATTCACAGGTAG-3′

Sequence B: 5′-GCATACCCAAATTAATAACGGCG
GTAGGCGACTCATTCTGATATACGCATCGGCAT
TTACCTACGGCCGGCCGGCCGGCCGGCCTAGA
TTTACCGCATTTACCGGCCGCATCGGATCGGG
ATTAGCATAATTAAAATGCATCGGCGTAGTAGG
CAATCGGCGCAGCCGAGCCACCTCCCGGAGAA
TCATCATCATCATCATCATCATCATCATCATCAT
CATCATACGGATAGATCCATTACCATGCGATTT
AAAGGCCATTCATGGGCCCCCGATTTATCCAT
TTAGGCCGGATTCCATGGATTCATTTCCATTTT
TCGGCATCATCATCATCATCATCATCATCATCA
TCATCATCATCATCATCAT-3′

(a) If these sequences code for the same protein, which gene is from a eukaryote? Why?
(b) How many promoter regions does each genome have? How can you identify them?
(c) How many copies of the gene are in each genome?

83. While investigating a strand of DNA, you identify three individuals who have a small change in one particular area. Using the following sequences, identify the types of mutations in the individuals. reference DNA: 5′-TCTATAGGA-3′ (7.5) K/U T/I

(a) individual A: 5′-TCTAAGGA-3′
(b) individual B: 5′-TCTATGGGA-3′
(c) individual C: 5′-TCTGGAGCTA-3′

84. Many products that we interact with and ingest have mutagenic effects. Two in particular—cigarettes and alcohol—have well-established links to cancer. Why are both of these products still sold, while other products are removed with less data to support their removal? Construct a one-page argument to either support or refute the continued sale of cigarettes and alcohol in Ontario. (7.5) T/I C A

Reflect on Your Learning

85. Suppose that you are watching the news and you hear the following statement: Genes code for enzymes. How would you react to hearing this statement? Explain your answer. K/U T/I

86. Garrod worked on heredity without knowing about DNA. Beedle and Tatum knew that DNA existed, but they did not know its structure or function. Does this information change your opinion about the need for an answer in all scientific experiments? Explain your reasoning. T/I A

87. What concept was the easiest for you to understand in this chapter? Why was it the easiest to understand? What did you do to understand it? How could you use your new knowledge to change your study habits? T/I C

88. Design a concept map to summarize your learning from this chapter. Use DNA as your starting point. K/U C

89. Has your impression of viruses changed after this chapter? Explain why or why not. K/U A

Research

WEB LINK

90. The "RNA world" hypothesis suggests that life existed with RNA before DNA evolved. Conduct research using the Internet and other sources to answer the following questions. T/I A

(a) What evidence supports this hypothesis?
(b) What properties of RNA would enable it to be the foundation of life?
(c) How could this hypothesis change our understanding of the origin of life on Earth?

91. Prokaryotes and eukaryotes have many similarities, including the use of ribosomes to synthesize proteins. However, there are subtle differences in the structure of their ribosomes. Research the structure of ribosomes and answer the following questions. T/I

(a) Use a method of your choice to summarize these differences.
(b) Erythromycin is often prescribed to treat bacterial infections. How does erythromycin disrupt bacterial ribosomes?

92. People often take antibiotics to treat viral infections. Research the effectiveness of antibiotics on bacterial and viral infections. Prepare a public service announcement or poster to advise people about this issue. T/I C

93. Vaccines have played an important role in the evolution of modern health care. In many cases, scientist have been able to develop vaccines to prevent the infection of a virus. However, the development of a vaccine for HIV has long eluded scientists. **Figure 2** shows the drugs that many HIV patients take daily to control the spread of the virus. Using the Internet, prepare a short summary of the quest to develop a vaccine for HIV. T/I C A

Figure 2

94. Some farmers are using a species of bacteria called *Pseudomonas syringae* to help them combat ice formation on their crops. *P. syringae* encourages the formation of ice crystals and rain. Farmers spray their crops with a genetically modified version of the bacteria to reduce the risk of frost damage. Research this topic by interviewing farmers on the issue (if possible) and using the Internet. Answer the following questions. T/I A
    (a) What ethical issues are associated with this practice?
    (b) How would you feel about consuming food that has been treated with *P. syringae*? Explain your thinking.
    (c) In your opinion, what actions or legislations should be in place for consumers?

95. The human epigenome project has a mandate to identify and determine the patterns of DNA methylation in the human population. Use the Internet to research the following questions. T/I C A
    (a) What is the epigenome?
    (b) What is a methylation variable position (MVP)?
    (c) Why do scientists want to focus their research on methylation?
    (d) Suppose that you have been put in charge of fundraising for the human epigenome project. Design a pamphlet that could be used to seek support from the general public for this project.

96. Skin cancer is the result of exposure of skin to ultraviolet light (**Figure 3**). There has been a recent push to ban teenagers from tanning salons in Ontario. This is backed by the World Health Organization's International Agency for Research on Cancer, which has labelled tanning beds as carcinogenic. Many schools have even pledged a tan-free prom since many teenagers believe that tanning salons are less of a risk than exposure to the Sun. Develop an informational poster, pamphlet, or infomercial for teenagers to educate them on the dangers of exposure to UV rays. Make sure to include the following:
    - how UV causes melanoma
    - why tanning beds and exposure to the Sun are the same
    - why humans darken when they tan T/I C A

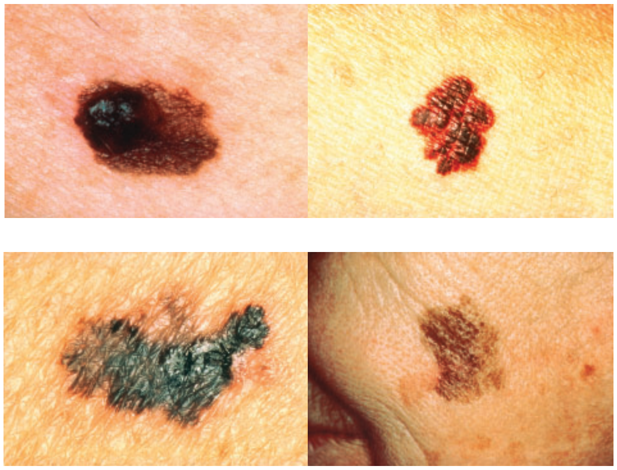


Figure 3 Signs of skin cancer

CHAPTER 8 Genetic Technologies

How Can Genes Be Biological Tools?

KEY CONCEPTS

After completing this chapter you will be able to

- describe how bacteria have provided many of the biotechnological tools that are used today, including restriction endonucleases and plasmids
- explain how transgenic plants and animals may increase pest and weed resistance in agriculture
- show how biotechnological applications can be used to clean up the environment
- describe biotechnology research that has led to advances in the field of medicine
- explain how forensic science uses biotechnology to place individuals at crime scenes and to verify identity
- explore the impacts of genetic engineering on health, society, and the environment

On April 20, 2010, in the Gulf of Mexico, a huge amount of methane under high pressure blew out of an underwater oil well, causing an explosion. For the next three months, oil leaked from the broken wellhead into the Gulf, causing an ecological disaster. Over 800 000 000 L of oil leaked into the ocean, damaging marine ecosystems, wildlife, beaches, and local economies.

Initially, traditional oil spill cleanup technologies were used to try to contain the spill. Thousands of workers scrubbed the oil from the sand on the beaches. Commercial fishers turned their trawlers into oil-skimming machines. Chemicals called dispersants, which break up oil droplets so that the oil does not stay as one big "slick" on the surface, were poured onto the spill. However, dispersants are also a form of pollution, and even dispersed oil damages the environment and its inhabitants.

Naturalists were concerned about the flocks of migratory birds that would fly south to the Gulf of Mexico in the fall. With toxins and oil slicks still in the water, millions of birds were expected to die. Fortunately, the migratory birds did better than expected. Residual oil is still a concern, however, especially for birds that breed on the beaches. The oil forms balls that are eaten by worms, so the toxins enter the food chain. Obviously, rapid non-invasive cleanup is the best option.

Nature had a few of its own solutions. Natural marine bacteria in the ocean broke down much of the methane and oil biologically in about six months. Conditions were almost optimal: water temperature was cold and only light crude oil was spewing from the well.

Scientists realized that if they could identify the gene that enables these bacteria to digest petroleum, they could isolate and study this gene, the proteins it produces, and the mechanisms these proteins use to digest hydrocarbons. This gene could possibly be introduced into the genomes of other types of bacteria that reside in other environments threatened by oil spills, such as soil or freshwater habitats.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills you will learn in the chapter.

1. Brainstorm a list of some of the molecular tools and techniques that a geneticist might use to remove a gene from one organism and insert it into another organism.
2. (a) What is gene therapy?
   (b) Do you believe that gene therapy will become, or should become, a major medical treatment?
3. You are probably familiar with the use of DNA fingerprinting technology, which is used to help solve crimes. What are some of the potential risks and benefits of such applications of DNA?
4. (a) Suggest possible advantages and disadvantages of genetically engineering plants and animals to produce large quantities of specific proteins.
   (b) What kinds of proteins might be particularly interesting to scientists?

Mini Investigation

Recognizing Palindromic Sequences

Skills: Performing, Observing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A2.1

One of the most useful tools in biotechnology uses restriction enzymes. Restriction enzymes scan double-stranded DNA for specific palindromic sequences and then cut the DNA into two fragments at these sequences. A palindrome reads the same forwards and backwards. For example, the words “civic” and “madam” are palindromes.

DNA palindromes work in a similar way. Consider the sequence 5′-GAATTC-3′. Its complementary strand is 3′-CTTAAG-5′. Notice that the complementary strand is a palindrome of the original strand (the same sequence as the original strand read backwards).

In this investigation, you will look for palindromic sequences in a hypothetical fragment of DNA.

1. Copy the following hypothetical sequence of DNA into your notebook:

   5′-AAGAATTCGCCAGAGTCTTGCTATGGACCTCAAGGTAGTGGCCAATACCGGGCCATGAATTCCGATACG-3′

A. Write out the sequence for the complementary DNA strand. K/U

B. Identify the palindromic sequences with four or more base pairs in the double-stranded DNA fragment. T/I

C. Using your knowledge of palindromes, write a six-base-pair sequence that is a palindrome. T/I

D. A palingram is a sentence that is palindromic. For example, “a tin mug for a jar of gum Nita” is read the same forwards and backwards. Create a palingram. T/I

E. Numbers can also be palindromes. For example, 1001 is a palindrome. Create a palindromic number using the following steps: T/I
   (i) Pick a number greater than 10.
   (ii) Reverse its digits, and add this value to the original number.
   (iii) If your result in (ii) is not a palindrome, repeat (ii) until you obtain a palindrome.

8.1 Manipulating and Cloning DNA

diabetes mellitus a disease in which the blood glucose level is too high because of the insufficient production or activity of the hormone insulin

type 1 diabetes a type of diabetes caused by an inability to produce insulin

type 2 diabetes a type of diabetes caused by low insulin or an inability to use insulin

Diabetes mellitus is a disease caused by a deficiency in the production of insulin, resulting in elevated blood glucose levels. Approximately 5 % of all deaths are caused by diabetes. **Type 1 diabetes** results when the body fails to produce insulin. Many people with type 1 diabetes require insulin by mouth or by injection to prevent the disease from seriously damaging their body. **Type 2 diabetes** results when the body does not produce enough insulin or when it cannot use the insulin produced. The two main risk factors associated with type 2 diabetes are a genetic predisposition and being overweight. In North America, type 2 diabetes is on the rise. Canadians eat more refined foods and sugar, and less natural foods and fibre, than ever before. As a consequence, more people are suffering from insulin resistance, obesity, and type 2 diabetes. Diabetes can lead to many health complications, including blindness, organ problems, limb amputations, and early death. You will learn about the differences between type 1 and type 2 diabetes in Unit 4.

Insulin was isolated by two researchers, Dr. Frederick Banting and Dr. Charles Best, at the University of Toronto in 1922. Helen Free, born a year after the discovery of insulin, invented a method to analyze the blood sugar by dip-test urinalysis. (Before this, doctors tasted a patient's urine. Sweet urine was an indicator of diabetes.) This allowed people with diabetes to monitor their blood sugar level easily at home. These two innovations have vastly improved the lives of diabetics.

genetic engineering the intentional production of new genes and alteration of genomes by the substitution or introduction of new genetic material

Insulin was initially collected from the pancreases of pigs and cows. Some people, however, had allergic reactions to this insulin, even though it was necessary to keep them alive. Scientists attempted to mass-produce actual human insulin. They discovered that they could insert the human insulin gene into bacteria, and the bacteria would make human insulin. **Genetic engineering** is the intentional alteration of a genome by substituting or introducing new genetic material into the genome. It is now used to mass-produce human insulin economically and safely.

recombinant DNA a DNA strand that is created using DNA pieces from two or more sources

Bacteria are versatile tools for genetic engineers because they reproduce quickly and often, are relatively inexpensive to maintain, and contain plasmids (small circular pieces of DNA that replicate independently of the bacteria's chromosome). The bacteria *Escherichia coli* (commonly known as *E. coli*) are very common in the human body and are used to produce biosynthetic human insulin. The human gene that codes for insulin is inserted into an *E. coli* plasmid. The *E. coli* transcribes and translates the piece of human DNA to make the human protein insulin, which is then harvested from the bacteria. Safflowers are also used to produce human insulin. After the human insulin gene in the plasmid is inserted into the *E. coli* or the safflower, the bacterial or plant DNA contains genes of two species and is called **recombinant DNA**.

Restriction Enzymes

restriction enzyme an enzyme that cuts DNA at a specific location in a base sequence; also called restriction endonuclease

recognition site a sequence of bases on a DNA strand that restriction enzymes bind to

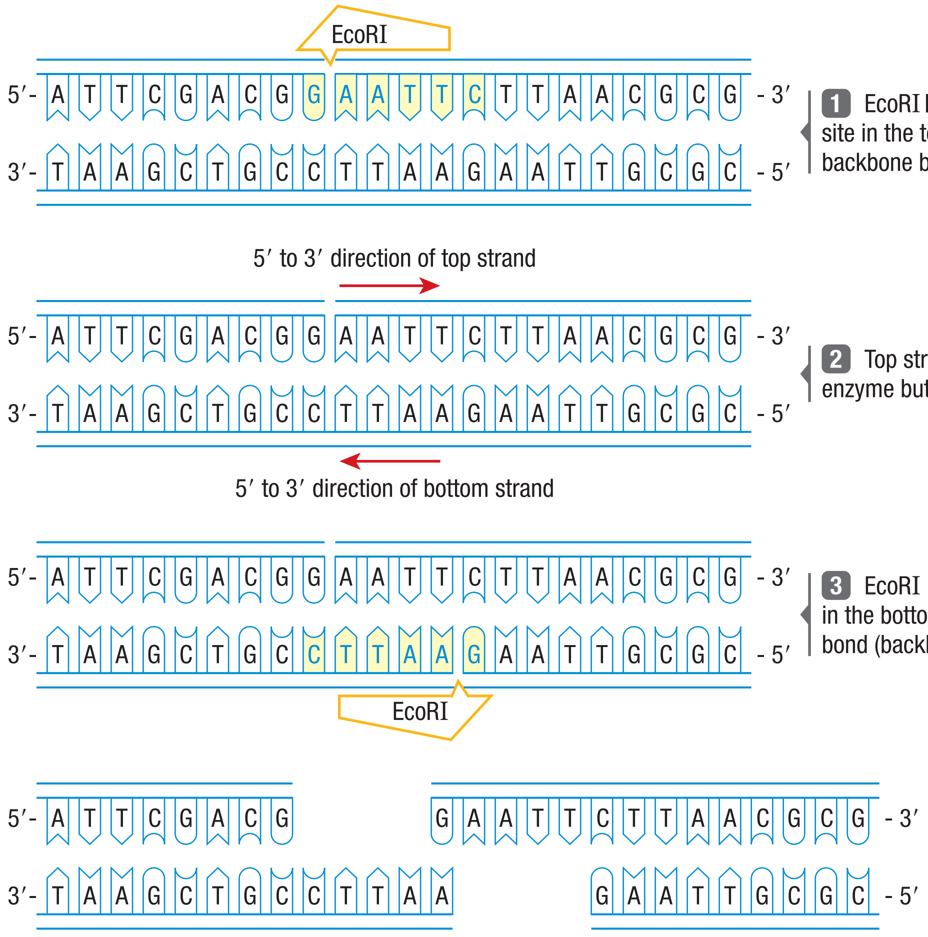
restriction fragment a fragment that is produced when a DNA strand is cut by a restriction enzyme

The first step in genetic recombination is to isolate, or cut out, a DNA fragment that contains the desired gene. Scientists use **restriction enzymes** (also called restriction endonucleases), which occur naturally in prokaryotic cells. A restriction enzyme acts like molecular scissors, cutting a DNA molecule at specific locations. Each restriction enzyme recognizes a specific sequence of nucleotides on a DNA strand. This is known as the **recognition site** for that particular enzyme. When the restriction enzyme cuts the DNA molecule, the pieces it creates are known as **restriction fragments**. Hopefully, one of the restriction fragments will contain the entire target gene, such as the gene for insulin.

Each restriction enzyme cuts (or digests) at only one recognition site and in only one direction. For example, the enzyme EcoRI binds to a recognition site with the base-pair sequence 5′-GAATTC-3′ (**Table 1** and **Figure 1**, next page). EcoRI then cuts the phosphodiester bond in the DNA backbone between the G and the A. Notice that the recognition sites on the DNA are palindromic when you consider both strands (Figure 1). Another EcoRI enzyme makes the same cut in the complementary DNA strand. This leaves only a small number of the hydrogen bonds holding the DNA molecule together, allowing the DNA molecule to be easily separated, resulting in complementary "sticky" ends.

Table 1 Examples of Restriction Enzymes

Enzyme name	Recognition site	End type	Outcome after restriction enzyme digestion
EcoRI	5′-GAATTC-3′ 3′-CTTAAG-5′	sticky	5′-G AATTC-3′ 3′-CTTAA G-5′
XhoI	5′-CTCGAG-3′ 3'-GAGCTC-5′	sticky	5′-G TCGAG-3′ 3′-GAGCT C-5′
HindIII	5′-AAGCTT-3′ 3′-TTCGAA-5′	sticky	5′-A TCGAC-3′ 3′-CAGGT G-5′
SmaI	5′-ACCCGGGT-3′ 3′-TGGGCCCA-5′	blunt	5′-ACCC GGGT-3′ 3′-TGGG CCCA-5′


EcoRI
5′- A T T C G A C G G A A T T C T T A A C G C G - 3′
3′- T A A G C T G C C T T A A G A A T T G C G C - 5′
5′ to 3′ direction of top strand
5′- A T T C G A C G G A A T T C T T A A C G C G - 3′
3′- T A A G C T G C C T T A A G A A T T G C G C - 5′
5′ to 3′ direction of bottom strand
5′- A T T C G A C G G A A T T C T T A A C G C G - 3′
3′- T A A G C T G C C T T A A G A A T T G C G C - 5′
EcoRI
5′- A T T C G A C G
G A A T T C T T A A C G C G - 3′
3′- T A A G C T G C C T T A A
G A A T T G C G C - 5′

1 EcoRI locates the 5′-GAATTC-3′ recognition site in the top strands and cuts the DNA backbone between the G and A bases.

2 Top strand has been cut by the restriction enzyme but the two strands remain together.

3 EcoRI locates a 5′-GAATTC-3′ recognition site in the bottom strand and cuts the phosphodiester bond (backbone), again between the G and A bases.

4 Both strands have been cut by restriction enzymes. The DNA separates into two fragments with "sticky ends."

Figure 1 How the restriction enzyme EcoRI cuts a DNA sequence

Two possible outcomes result from a restriction enzyme cutting a DNA molecule. If cuts are made straight across the strand, **blunt ends** are created. If cuts are made in a zigzag, **sticky ends** are created. For example, EcoRI produces sticky ends, whereas SmaI produces blunt ends (Table 1). Molecular biologists prefer to work with restriction enzymes that produce sticky ends because the DNA fragments that are created are easier to join to any other DNA strand that has been cut by the same enzyme.

In 1970, Dr. Hamilton Smith, of Johns Hopkins University School of Medicine, was wondering how some bacteria resisted viral infections when he accidentally discovered restriction enzymes. Since then, many such enzymes have been catalogued. At least 2500 restriction enzymes, with specificity for about 200 target sequences, have been isolated, mostly from prokaryotic cells. About 200 of the most helpful restriction enzymes are available commercially for use in molecular biology laboratories. WEB LINK

blunt end the end that remains after restriction enzymes cut straight across a DNA strand; a blunt end is more difficult than a sticky end to recombine with another strand

sticky end the end that remains after restriction enzymes cut on a zigzag across a DNA strand; a sticky end of a DNA fragment can form hydrogen bonds with a complementary sticky end on any other DNA molecule that has been cut by the same enzyme

The biological function of restriction enzymes is to protect the cells in which they are found. When a virus injects its own DNA or RNA into a bacterial cell, the bacterial restriction enzymes destroy the viral nucleic acid by cutting it in pieces. The fact that scientists can use this function of restriction enzymes for DNA technology is indeed fortunate!

Restriction enzymes are highly specific. Most have recognition sites for four to eight base pairs. The fewer base pairs that they need for the recognition sequence, however, the more cuts that are made in a DNA strand. In a random DNA sequence, the probability of finding a particular four-pair sequence is one in 4^4 ($\frac{1}{256}$ or 0.4 %). The chance of finding the six-pair sequence that EcoRI needs to perform a cut is one in 4^6 ($\frac{1}{4096}$ or 0.02 %).

A restriction enzyme is named after its cell of origin, plus a Roman numeral if more than one restriction enzyme has been isolated from this species. For example, EcoRI (pronounced "eco-R-one") was the first restriction enzyme isolated from *E. coli*, XhoI was the first enzyme isolated from *Xanthomonas holcicola*, and HindII and HindIII were the second and third enzymes isolated from *Haemophilus influenzae*.

DNA Ligase

DNA ligase is the enzyme that is used to join cut strands of DNA (Section 6.4). DNA ligase works best with sticky ends of DNA, but a second form, T4 DNA ligase, works well with blunt ends. The two DNA fragments must have overlapping complementary portions or be blunt ends that are properly aligned end to end. They will be complementary if they were both generated using the same restriction enzyme, since each restriction enzyme cuts specifically at one sequence of base pairs.

Hydrogen bonds form between the complementary bases, but this is not a stable arrangement. The DNA is not fully linked until phosphodiester bonds form between the backbones of the double strands. DNA ligase is the enzyme that makes this happen. DNA ligase works, as many organic reactions do, by promoting a dehydration reaction. Thus, water molecules are released when DNA ligase joins the DNA strands.

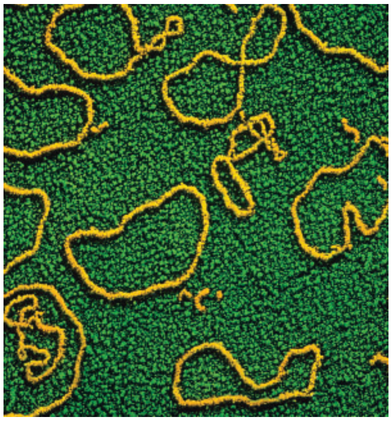


Figure 2 This electron micrograph shows plasmids inside *E. coli.*

Plasmids

The next tools that are needed for recombinant DNA techniques are plasmids, small circular pieces of DNA that are found in bacteria (**Figure 2**). Plasmids replicate independently of the chromosomal DNA. They often contain genes that code for specific proteins, such as proteins that provide resistance to antibiotics such as ampicillin or protect from the toxic effects of certain heavy metals. In fact, when you hear about bacteria that mutate quickly so that diseases become difficult to treat, it is often the plasmid DNA that is mutating.

competent cell a cell that is able to take up foreign DNA from its surroundings

vector a DNA molecule that is used as a vehicle to transfer foreign genetic material into a cell, for example, a plasmid

copy number the number of plasmids of a specific type within a cell

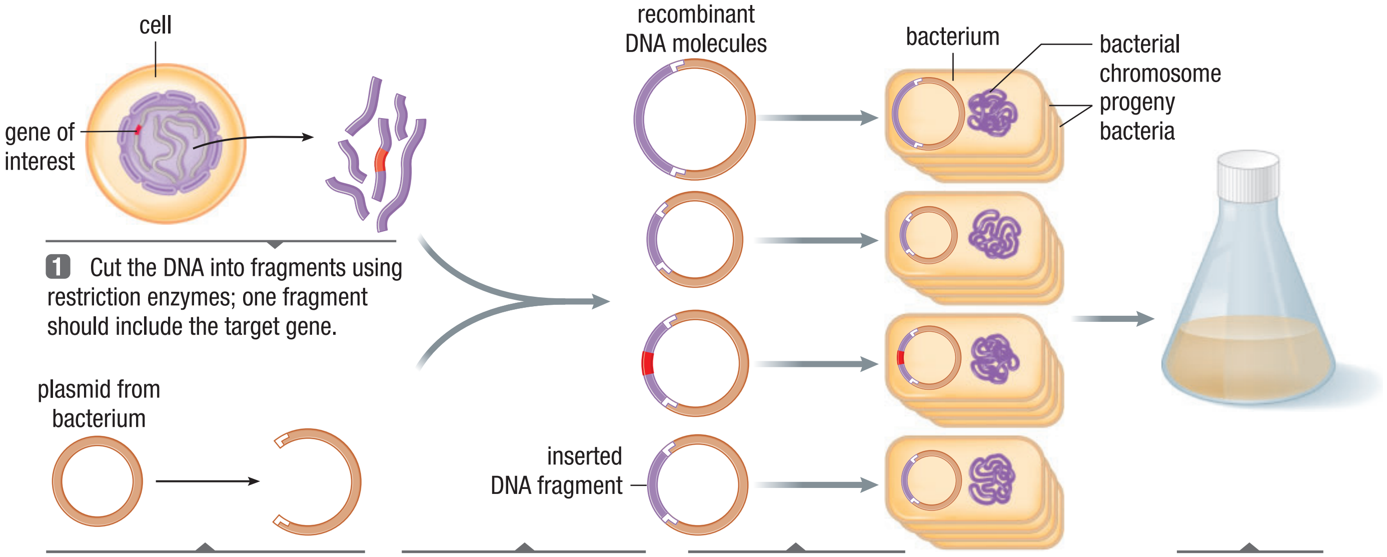
A cell that is able to take up foreign (often plasmid) DNA, such as a healthy *E. coli* cell, is called a **competent cell**. A plasmid that has been designed to be a vehicle for transferring foreign genetic materials into a cell is called a **vector**. The plasmid **copy number**, the number of copies of a plasmid within a bacterial cell, is variable and is characteristic of a particular plasmid. If a plasmid with a high copy number has been engineered to produce insulin, more insulin will be produced per cell because more copies of the insulin-producing gene are present.

host cell a cell that has taken up a foreign plasmid or virus and has used its cellular machinery to express the foreign DNA

cloned gene an identical copy of an original target gene that can be made by introducing the target gene into a host cell and having it copied

If a fragment containing a target gene is created using the same restriction enzyme that a plasmid is cut with, the fragment will possess the same complementary ends as the linear plasmid. The foreign fragments and the plasmid fragments can be placed in the same solution, where they anneal because of the complementary sticky ends. DNA ligase is then added to re-form the phosphodiester bonds between the fragments, resulting in a new circular piece of DNA that carries the foreign gene fragment. The plasmid is now recombinant DNA, a combination of the original plasmid DNA and the foreign DNA. The plasmid can be introduced into a **host cell** (often a bacterial cell), where it will replicate to form many copies within the cell. The gene has been cloned because, as the plasmid replicates, many copies of the plasmid with recombinant DNA will be produced. **Cloned genes** are identical multiple copies of a gene. Each copy of the plasmid will include a copy of the original inserted gene. The gene can now begin to express its function. For example, if the insulin gene is in the plasmid, the host cell will begin to produce insulin.

The procedure that is used by researchers to verify that bacteria are carrying a target gene is outlined in **Figure 3**. Refer back to this figure as you continue. Later in this section, you will learn how the bacteria with the target gene are identified (hybridization).



1 Cut the DNA into fragments using restriction enzymes; one fragment should include the target gene.

2 Use an artificial engineered plasmid that is antibiotic resistant and has a multiple cloning site. Cut the circular plasmid to make it linear.

3 Insert a gene fragment into each plasmid to make recombinant DNA. The recombinant DNA molecule is the recombinant plasmid.

4 Transform bacterial cells with recombinant DNA plasmids. Each bacterium receives a different plasmid. As the bacteria divide, the recombinant plasmids replicate, amplifying the piece of DNA inserted into the plasmid.

5 Identify the bacterium containing the plasmid with the target gene inserted into it.

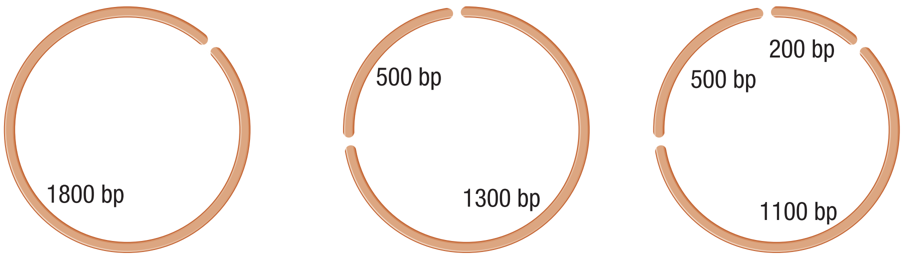
Figure 3 An overview of cloning DNA fragments in a bacterial plasmid

Restriction Maps

Plasmid mapping has revolutionized molecular biology. A **restriction map** is a diagram that shows the relative locations of all the known restriction enzyme recognition sites on a particular plasmid and the distances, in base pairs (bp), between the sites. This technique allows molecular biologists to determine which plasmids might be most suitable for a particular recombinant DNA procedure and to evaluate quickly the success of the cloning experiments.

Scientists often use a restriction map to determine which restriction enzyme they will use to cut the plasmid. **Figure 4** shows a restriction map that illustrates two recognition sites for the restriction enzyme EcoRI and one site for HindIII. This map also shows the number of base pairs between the cut locations of each enzyme. When added up, we can see that the plasmid has a total length of 1800 base pairs.

Figure 5 shows the results of exposing the plasmid in Figure 4 to the two restriction enzymes on their own and in combination. EcoRI cuts the plasmid in two



(a) 1 fragment: 1800 bp

(b) 2 fragments: 500 bp, 1300 bp

(c) 3 fragments: 200 bp, 500 bp, 1100 bp

Figure 5 Plasmid digestion with (a) HindIII only, (b) EcoRI only, and (c) EcoRI and HindIII

restriction map a diagram that shows restriction enzyme recognition sites and the distances, measured in base pairs (bp), between the sites

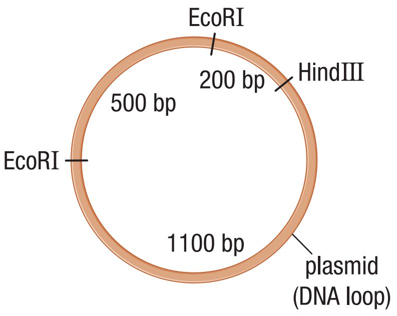


Figure 4 A simple example of a restriction map

locations and produces two fragments, while HindIII cuts the plasmid in only one location and produces one fragment. When the plasmid is exposed to both restriction enzymes, three fragments are produced. Because plasmids are circular, the number of fragments is always equal to the number of cuts. In the following tutorial, you will construct restriction maps from the given information.

Tutorial 1 Constructing Restriction Maps

A restriction map shows restriction enzyme recognition sites and the distances, measured in base pairs (bp), between the sites. You have learned how a restriction map can be used to predict the fragment lengths that will be produced by different digestions. In this tutorial, you will learn how geneticists use restriction enzymes to gather data and construct a restriction map.

Sample Problem 1: Constructing a Restriction Map to Show Recognition Sites

Construct a restriction map for Plasmid X to show the recognition sites for two commonly used restriction enzymes: EcoRI and BamHI.

Step 1. First, two separate restriction enzyme digestions are performed on different samples of Plasmid X (two single digestions). Then a double digestion is performed on the plasmid with both restriction enzymes. After the digestions are performed, the fragment lengths are determined (**Table 2**). (This is done using gel electrophoresis, which you will learn about later in the chapter.) The length of the undigested plasmid is also determined. Notice that the sum of the fragments is always equal to the total length of the plasmid.

Table 2 Results of Plasmid X Digested with EcoRI and BamHI

Plasmid X undigested	Plasmid X digested with EcoRI	Plasmid X digested with BamHI	Plasmid X digested with EcoRI and BamHI
1400 bp	1400 bp	600 bp 800 bp	100 bp 600 bp 700 bp

Step 2. Draw Plasmid X restriction maps for the individual restriction enzymes (**Figure 6**).

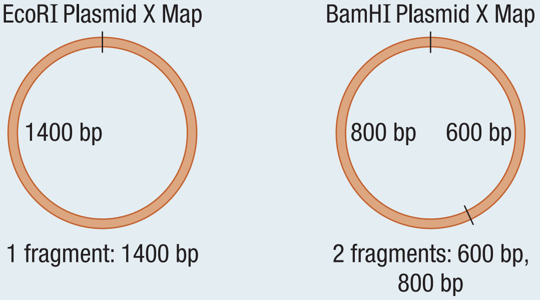


Figure 6

Step 3. Draw a restriction map for all the restriction sites.

We do not know the location of the EcoRI recognition site relative to the BamHI sites. However, we do know the fragment lengths for the combined digestion (column 4 of Table 2). We can use this information to determine the relative locations of the restriction sites.

First, we redraw a restriction map for one of the single digestions. It is easier to begin with the digestion that produced the greater number of fragments, so we redraw the BamHI map (**Figure 7(a)**, next page).

Next, we consider the fragment lengths produced by the double digestion. Note the following:

- There are two new fragment lengths: 100 bp and 700 bp
- One fragment length is unchanged: 600 bp

Since we now have a fragment of only 100 bp in length, we know that the EcoRI site must be within 100 bp of a BamHI cut. Such a cut could occur within the 600 bp or 800 bp fragment (**Figure 7(b)**). However, because we also know that the remaining two fragments are 600 bp and 700 bp, we can infer that the EcoRI site is located within the 800 bp fragment. The final restriction map is shown in **Figure 7(c)**.

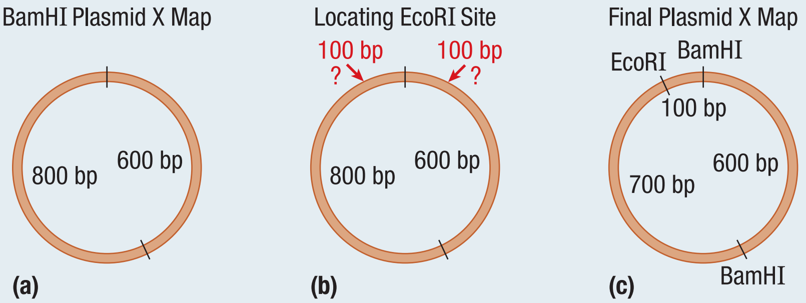


Figure 7

Sample Problem 2: Constructing a Restriction Map Using Digestion Fragment Length Data

Construct a restriction map, beginning with data already obtained from the digestion of Plasmid Y using the restriction enzymes EcoRI and BamHI. The data are provided in **Table 3**.

Table 3 Results of a Restriction Fragment Digestion of Plasmid Y

EcoRI	BamHI	EcoRI + BamHI
600 bp 1200 bp	600 bp 1200 bp	200 bp 200 bp 400 bp 1000 bp

Step 1. Draw Plasmid Y restriction maps for the individual restriction enzymes. The results of the first two digestions are shown in **Figure 8**.

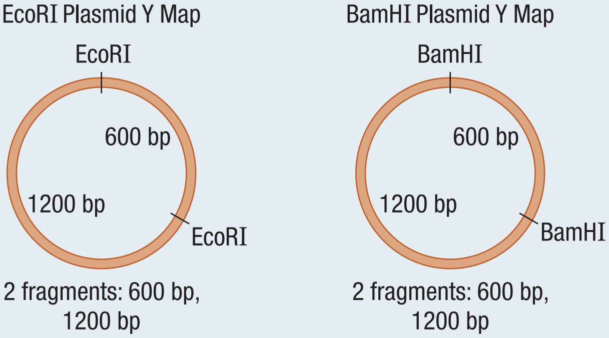


Figure 8

Although the fragment lengths produced by both digestions are the same, we know that each restriction enzyme recognizes different base-pair sequences. Therefore, these sites are not at the same positions on the plasmid.

Step 2. Draw a restriction map of all the restriction sites.

First, we redraw one of the restriction maps for a single digestion (**Figure 9(a)**).

Next, we consider the fragment lengths that are produced by the double digestion: 200 bp (2), 400 bp, and 1000 bp.

Using logic, we can infer the following:

- One BamHI site must be within the 600 bp EcoRI fragment, and the other must be within the 1200 bp EcoRI fragment. (There are no 600 bp or 1200 bp fragments remaining after the double digestion.)
- Both BamHI cuts produce a fragment of 200 bp, and they are 600 bp apart. (Since there is no 400 bp fragment to begin with, we know that a single cut cannot produce both 200 bp fragments.)

Based on this logic, we can infer that one cut is 200 bp from an EcoRI site and within the 600 bp fragment (**Figure 9(b)**). This cut creates a 200 bp fragment and a 400 bp fragment. The second BamHI site must be located 600 bp away from the first site, but closer to the second EcoRI site in order to produce a second 200 bp fragment. The final restriction map is shown in **Figure 9(c)**.

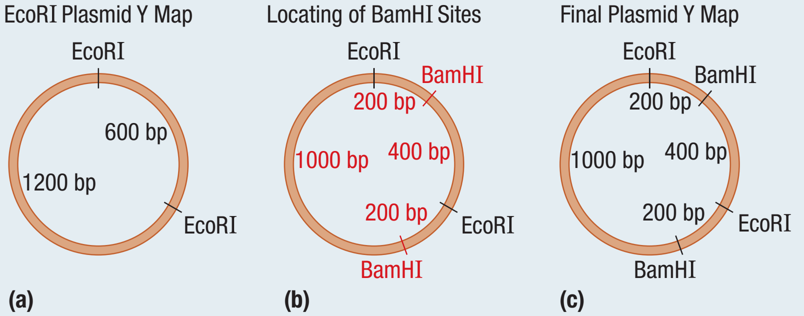


Figure 9

Practice

1. Plasmid Z has yet to be mapped. It was digested with two enzymes: EcoRI and PstI. The following data were obtained (**Table 4**).

Table 4 Results of a Restriction Enzyme Digestion of Plasmid Z

Plasmid Z uncut	Plasmid Z cut with EcoRI	Plasmid Z cut with PstI	Plasmid Z cut with EcoRI and PstI
1500 bp	500 bp 1000 bp	1500 bp	300 bp 500 bp 700 bp

(a) In how many locations did EcoRI cut Plasmid Z? Did PstI cut Plasmid Z?
(b) Draw the restriction map for Plasmid Z.

2. Plasmid W has yet to be mapped. It was cut with two enzymes: HindIII and BamHI. The following data were obtained (**Table 5**).

Table 5 Results of a Restriction Enzyme Digestion of Plasmid W

Plasmid W uncut	Plasmid W cut with HindIII	Plasmid W cut with BamHI	Plasmid W cut with HindIII and BamHI
1000 bp	450 bp 550 bp	400 bp 600 bp	150 bp 250 bp 300 bp 300 bp

(a) In how many locations did HindIII cut Plasmid W? Did BamHI cut Plasmid W?
(b) Draw the restriction map for Plasmid W.

3. Plasmid Q is known to contain recognition sites for three restriction enzymes. To prepare a restriction map for this plasmid, researchers performed seven different digestions, including single, double, and triple digestions. Use the data in **Table 6** to generate a final restriction map, showing the relative locations of all the restriction enzyme recognition sites.

Table 6 Results of a Restriction Fragment Digestion of Plasmid Q

EcoRI	BamHI	SmaI	EcoRI + BamHI	EcoRI + SmaI	BamHI + SmaI	EcoRI + BamHI + SmaI
800 bp 1500 bp	250 bp 700 bp 1350 bp	900 bp 1400 bp	200 bp 250 bp 300 bp 500 bp 1050 bp	350 bp 450 bp 450 bp 1050 bp	150 bp 250 bp 550 bp 600 bp 750 bp	150 bp 200 bp 250 bp 300 bp 350 bp 450 bp 600 bp

Transformation

Under specific conditions, plasmids enter bacterial cells, multiply, and express the foreign gene that has been inserted into the plasmid genome. The successful introduction of DNA from another source is called transformation (Section 6.2). The cell that has received the DNA is said to be transformed.

If a bacterial cell is not able to take up a plasmid that contains foreign DNA, it can sometimes be made competent in a laboratory. One way to do this is to place the bacteria in a solution that contains calcium chloride and recombinant plasmids in an ice-water bath. As the bacteria cool, the calcium ions stabilize the negative phosphate ions on the phospholipid bilayer of the cell membrane. The $CaCl_2$ solution is then heated quickly and re-cooled. The sudden change from cold to hot momentarily disrupts the membrane, allowing the plasmid to enter (**Figure 10**). The cells are then kept at 37 °C for a period of time to stabilize and grow.

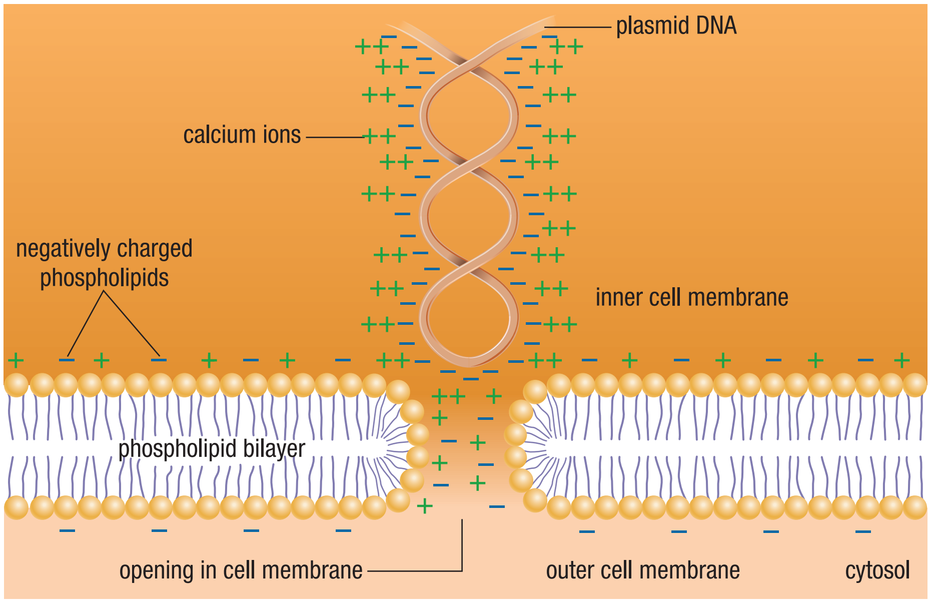


Figure 10 Calcium ions neutralize the negative charge from the phosphate group on the plasmid DNA and on the phospholipids found in the cell membrane. This minimizes the repelling effect of like charges. DNA can then enter the bacterial cell more easily.

Investigation **8.1.1**

Transformation of Bacteria with the Gene for Green Fluorescent Protein (p. 399)

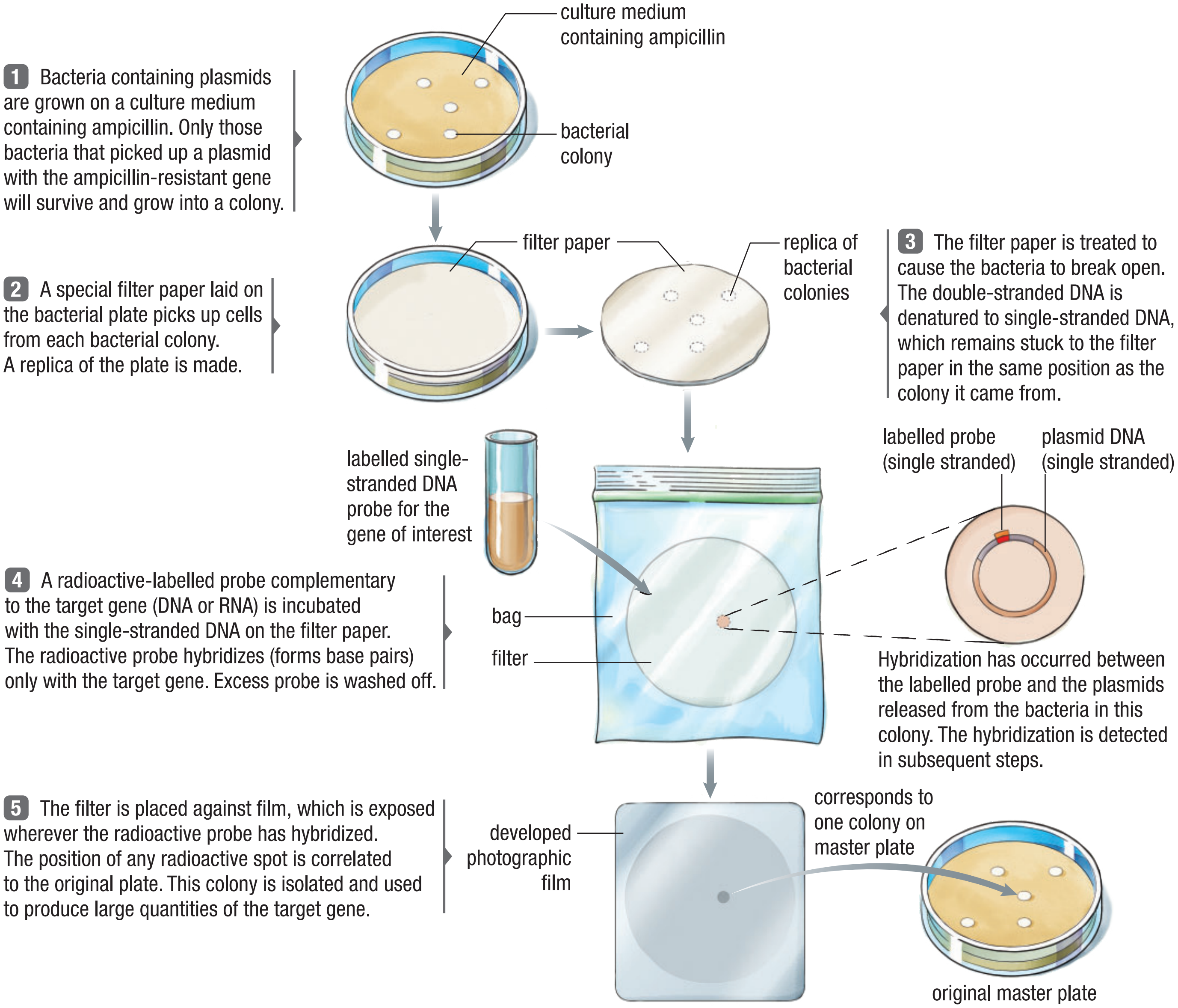
Now that you have learned what genetic engineers do to produce genetically modified bacteria, you can perform Investigation 8.1.1 and genetically engineer bacteria yourself.

After the cells have stabilized and grown, they are tested for ampicillin resistance. Those that contain a plasmid with the gene for ampicillin resistance grow in a medium that contains ampicillin. This means that they were successfully made competent and transformed. If they do not grow and replicate, they do not contain the plasmid with the ampicillin-resistant gene, so the process was unsuccessful.

Hybridization: Identifying Bacterial Clones with Target Genes

The technique of DNA hybridization is used to identify the cells that contain the introduced plasmids with the desired gene. This gene can be identified by its unique DNA sequence because it will pair with a short, single-stranded complementary DNA molecule, called a **hybridization probe**. For the gene with the recombinant DNA for insulin production, the hybridization probe is a piece of the DNA that codes for insulin, ranging in size from 15 to 2500 bases. **Figure 11** shows the steps taken to identify a target DNA sequence during DNA hybridization. After the presence of the DNA for insulin production is confirmed, the bacteria are grown in huge quantities, enough to produce insulin on a commercial scale.

hybridization probe a fragment of DNA that is used to detect the presence of complementary nucleotide sequences


culture medium containing ampicillin
bacterial colony
filter paper
replica of bacterial colonies
labelled single-stranded DNA probe for the gene of interest
labelled probe (single stranded)
plasmid DNA (single stranded)
bag
filter
developed photographic film
corresponds to one colony on master plate
original master plate

1 Bacteria containing plasmids are grown on a culture medium containing ampicillin. Only those bacteria that picked up a plasmid with the ampicillin-resistant gene will survive and grow into a colony.

2 A special filter paper laid on the bacterial plate picks up cells from each bacterial colony. A replica of the plate is made.

3 The filter paper is treated to cause the bacteria to break open. The double-stranded DNA is denatured to single-stranded DNA, which remains stuck to the filter paper in the same position as the colony it came from.

4 A radioactive-labelled probe complementary to the target gene (DNA or RNA) is incubated with the single-stranded DNA on the filter paper. The radioactive probe hybridizes (forms base pairs) only with the target gene. Excess probe is washed off.

Hybridization has occurred between the labelled probe and the plasmids released from the bacteria in this colony. The hybridization is detected in subsequent steps.

5 The filter is placed against film, which is exposed wherever the radioactive probe has hybridized. The position of any radioactive spot is correlated to the original plate. This colony is isolated and used to produce large quantities of the target gene.

Figure 11 DNA hybridization to identify the presence of a target gene

8.1 Review

Summary

- Insulin can be produced by genetically engineering bacterial cells and then cloning them.
- Appropriate restriction enzymes are used to remove and create a relatively small DNA fragment containing the target gene from the original DNA.
- To construct a recombinant DNA molecule, the target gene is inserted into a DNA vector. Plasmids are one example of a vector.
- Bacterial host cells can be manipulated to take up foreign DNA using a calcium chloride transformation.
- A restriction map is a diagram that shows distances (in base pairs) between restriction enzyme recognition sites.
- Cells that have been successfully transformed with recombinant DNA are isolated based on their ability to resist an antibiotic. Those that contain plasmids with the target gene are identified using hybridization techniques.

Questions

1. Create a flow chart to show how a piece of DNA containing a target gene is excised, combined with a plasmid, and then expressed by a host cell. K/U C
2. HindIII and SmaI are used to cut up samples of a large piece of DNA (Table 1, page 367). Which enzyme would you expect to produce the larger number of fragments? Explain your reasoning using mathematics. T/I C
3. Why are restriction enzymes that produce DNA fragments with sticky ends more valuable to geneticists than restriction enzymes that produce DNA fragments with blunt ends? K/U
4. What are the benefits of a bacterial cell that contains a plasmid? K/U
5. Why is a test performed to determine whether transformed cells are antibiotic resistant before they are isolated and grown? K/U
6. A fragment of DNA is 120 000 base pairs long and is cut by a restriction enzyme with a recognition site that is five base pairs long. How many cuts would you expect? T/I
7. Using the Internet or other sources, find an actual restriction map. Copy the restriction map into your notebook. Locate and label the antibiotic-resistant gene and the multiple cloning site, if it exists. Identify one restriction enzyme that would create a single fragment and, if applicable, one restriction enzyme that would cut the fragment into two pieces. 🌐 T/I C
8. The plasmid in **Figure 12** was digested using different restriction enzymes whose sites have been mapped. The plasmid is 7896 base pairs long and contains a gene (shown in green) that confers antibiotic resistance to tetracycline. T/I A

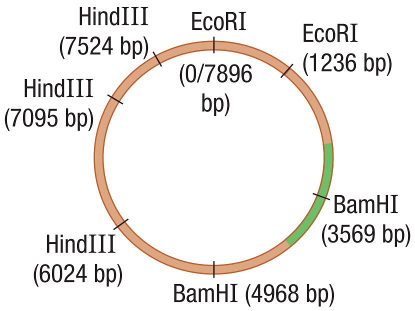


Figure 12

(a) Determine the size and number of fragments that would be produced if the plasmid was digested with the following enzymes:
   (i) EcoRI
   (ii) BamHI
   (iii) HindIII
   (iv) EcoRI and HindIII
   (v) EcoRI, HindIII, and BamHI

(b) Which cut would inactivate the antibiotic resistance? Why?

WEB LINK

8.2 DNA Sequencing

At one time, lake sturgeon were abundant in many lakes across Canada (**Figure 1**). Currently, however, due to overfishing for their meat and caviar, sturgeon populations are on the decline in many areas. There are serious penalties for fishing and eating this endangered species of fish, and conservation officers now have a reliable tool to help them enforce the ban: DNA.

Figure 1 An ancient species, lake sturgeon are Canada's largest freshwater fish. They can grow up to 2 m long and weigh up to 135 kg. Today, however, specimens of this now-endangered species are much smaller.

The lake sturgeon is a protected species under the federal Fisheries Act, and violators of hunting and fishing regulations can be prosecuted. If conservation officers come across campers eating fish, and they suspect that the fish is not in season or is an endangered species, they can take a small sample to a forensic lab. If the DNA matches that of a banned species, the conservation officers have sufficient evidence to give to the police.

Trent University, in Ontario, has a Wildlife DNA Profiling and Forensics Laboratory. One of the major duties of this laboratory is to track and monitor endangered species and support the enforcement of the Convention on International Trade in Endangered Species of Wild Flora and Fauna (CITES). Thanks to a procedure called the polymerase chain reaction (PCR), developed in 1983 by Kary Mullis in California, conservation officers and forensic scientists do not need a large sample of DNA in order to run extensive DNA fingerprinting tests. These tests can be used to identify the species of fish on someone's plate or the source of blood on a hunting knife, or to place a perpetrator at the scene of a crime. CAREER LINK

In this section, you will learn about several molecular biology techniques that can be used to analyze DNA and identify the species that was the source of the DNA.

The Polymerase Chain Reaction

polymerase chain reaction (PCR) a process that is used to make a huge number of copies of a DNA sequence in a laboratory, quickly and without the need for a host organism

The **polymerase chain reaction (PCR)** is a powerful process that can greatly increase the number of copies of DNA from one biological sample in just a few hours. It is important to note that a whole genome of DNA is not replicated using PCR, but a specific region of the chromosome. The PCR method is elegant in its simplicity, making it reliable, fast, and inexpensive; thus, it is in widespread use. PCR has made an enormous difference to molecular biology, and consequently to society. For his innovation, Kary Mullis was awarded the Nobel Prize in Chemistry in 1993.

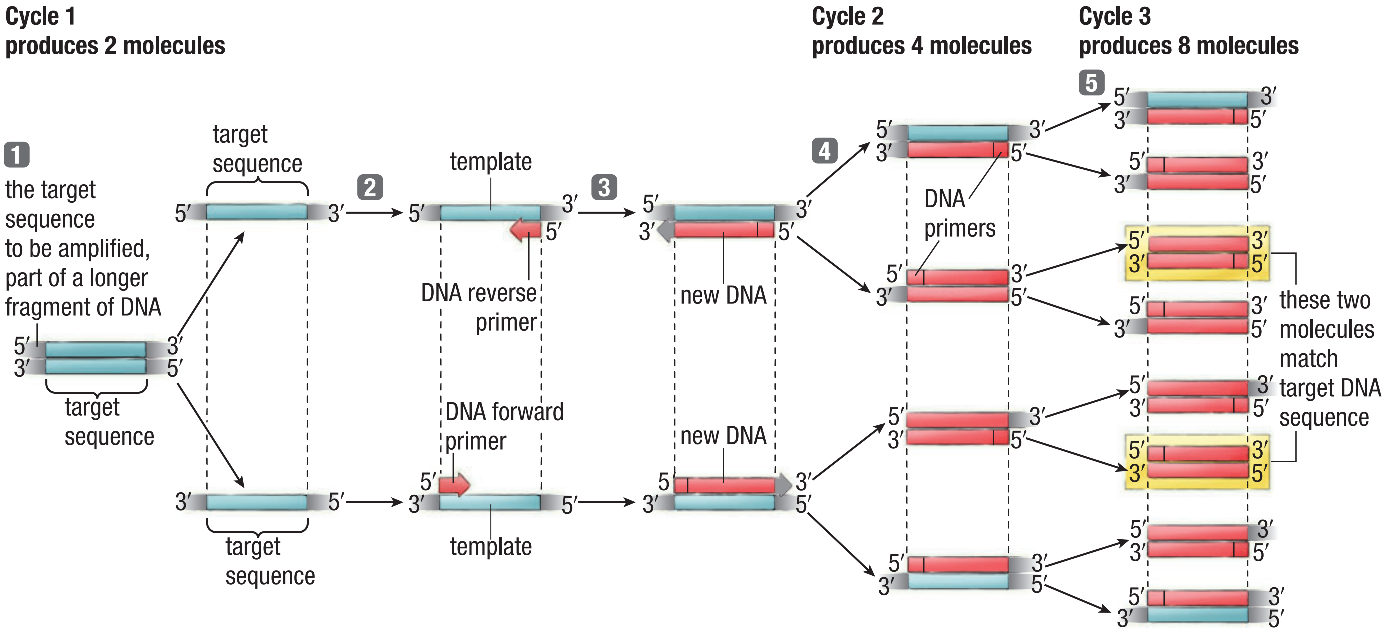
PCR is DNA replication of a specific region of the genome, outside of the nucleus of a cell, in a laboratory setting. The whole process takes place in a microfuge tube (a small test tube) and consists of three steps: denaturation, annealing, and elongation. These steps are repeated in many cycles, usually 30 to 40 (**Figure 2**, next page). WEB LINK

In the first step, called denaturation, a double-stranded DNA molecule is denatured, or separated, into its two single strands. This occurs when the DNA strand is heated to 94 to 96 °C for 20 to 40 s, causing the hydrogen bonds holding the two strands together to break. (Recall that the purines and pyrimidines in DNA are held together by hydrogen bonds.)

DNA primer a short single-stranded DNA sequence, easily synthesized in a laboratory, that is complementary to a sequence at one end of the target sequence

The second step, called annealing, takes place at a lower temperature, from 50 to 65 °C, for 20 to 40 s. This step facilitates the annealing of synthesized single-stranded **DNA primers** to each of the separated single strands. The primers contain the nucleic acid sequence that is complementary to one end of the targeted fragment of DNA. Two DNA primers are used: one must be complementary to a short portion of DNA on one strand at, or near, a 3′ end of the target sequence, and the other primer must be complementary to a portion of DNA on the other strand at the opposite 3′ end of the target strand. This results in both primers being oriented in the 5′ to 3′ direction toward the target sequence. The specificity of the primers results in the amplification of only the target sequence of the DNA, making the PCR technique highly specific.

In the third step, called elongation or extension, two new DNA strands are synthesized at a temperature of 72 °C. The two original DNA strands, which were separated



1 Denaturation: Heat a DNA fragment containing the target sequence to 94–96 °C to denature it to single strands.

2 Annealing: Cool the mixture to 50–65 °C to allow the forward and reverse primers to anneal to their complementary sequences at the two ends of the target sequence.

3 Elongation: Heat to 72 °C for DNA polymerase to extend the primers using free-floating nucleotide precursors to make complementary copies of each template strand.

4 Cycle 2: Repeat Steps 1, 2, and 3. Four molecules are produced.

5 Cycle 3: Repeat the same steps again, producing a total of eight molecules. Two of the eight match the exact length of the target DNA sequence (highlighted in yellow).

Figure 2 The PCR process has three steps (1, 2, and 3), which are repeated (4 and 5). Beginning with a DNA fragment that contains the target sequence, the process ends up with DNA fragments that exactly match the target sequence, with no extra base pairs.

in the first step, now act as templates. DNA polymerase binds to the primer-template hybrids and moves along each template, adding nucleotides that are complementary to the sequence until it reaches the 5′ end of the template.

A very specific DNA polymerase, called Taq polymerase, is needed for PCR elongation. Taq polymerase is extracted from the bacterium *Thermus aquaticus*. This bacterium is found in hot springs, so its enzymes can withstand high temperatures. The use of Taq polymerase is vital since it is not denatured by the high temperature that is used during the first step of PCR. This would not be the case with DNA polymerase from a typical organism.

After the two double-stranded DNA sequences have been made (at the end of Step 3 in Figure 2), the process can run through another cycle. The temperature is elevated back to 94 °C, and the strands are denatured again. Four strands are used as templates and duplicated to produce new copies. This cycle is repeated 30 to 40 times, resulting in a high number of copies of the specific target sequence.

By the third cycle, two of the eight DNA molecules exactly match the target molecules. As shown in Figure 2 (Step 5), the small piece of DNA at each end of the target sequence is eventually lost, and the target DNA sequence vastly outnumbers any other sequence. Within 20 cycles, the PCR reaction delivers over one million copies of the DNA target sequence. Since each cycle, regulated simply by increasing and decreasing the temperature, takes only about 5 min, millions of copies of a DNA sequence can be synthesized in less than 2 h! PCR is such an efficient process that it is used almost exclusively to amplify a target DNA sequence. As mentioned earlier, it is the process that is used by Fish and Wildlife personnel to identify a species of fish from a minute sample. The equipment that performs the rapid temperature changes and the various enzymes and primers are all available commercially.

WEB LINK

As you have learned, PCR can make millions of copies of a single segment of DNA very quickly. This means that only a very small amount of a biological sample is required. There is enough DNA in a hair follicle, a tiny blood spatter, or a tiny piece of fish tissue to perform PCR. Once the DNA of interest has been amplified using PCR, it is analyzed using different methods. These methods are described on the next few pages.

Gel Electrophoresis

gel electrophoresis a method for separating large molecules, such as DNA, RNA, and proteins

Once the targeted DNA sequence has been amplified by PCR, it needs to be separated and purified from the rest of the contents in the test tube. A chromatography-like process, called **gel electrophoresis**, uses the physical and chemical properties of DNA to separate the fragments.

Gel electrophoresis separates nucleic acids and proteins by their rate of migration through a gel. Agarose gel, made from agar (a polysaccharide from seaweed), is normally used for nucleic acids. Negatively charged DNA fragments travel through the pores of the gel, away from a negative electrode at the starting end and toward a positive electrode at the destination end. Recall that DNA is negatively charged, due to the phosphate groups, and is therefore attracted to a positive electrode. Because of the negative charge that is carried by the phosphate groups, each nucleotide is ionized. This means that nucleic acids have about the same charge-to-mass ratio, even if they differ in length. The smaller fragments of nucleotides move more easily, and hence faster, through the pores of the gel than the longer fragments do. Therefore, DNA fragments can be separated by size. The smaller the fragment, the farther it travels in a given period of time.

Figure 3 shows the four steps in gel electrophoresis. The numbered steps here refer to the numbers in Figure 3.

Step 1. Prepare a gel (a thin slab of agarose), and place it in a gel box between two electrodes. The gel has wells for placing the DNA samples to be analyzed. Add a buffer to cover the gel.

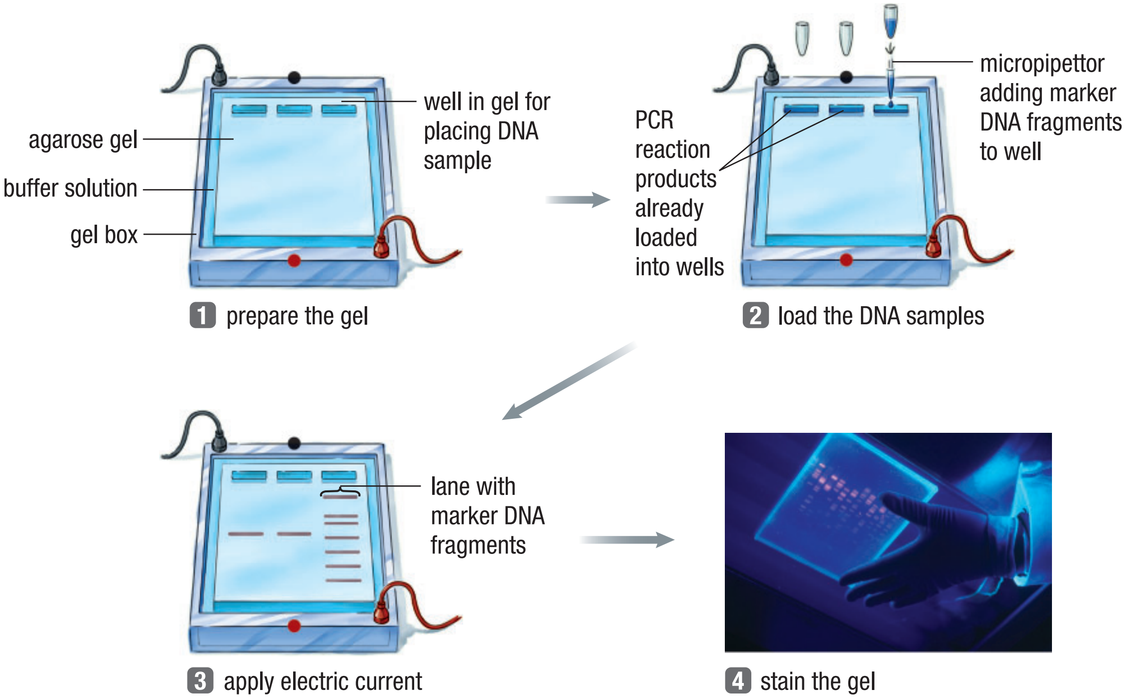

agarose gel
buffer solution
gel box
well in gel for placing DNA sample
PCR reaction products already loaded into wells
micropipettor adding marker DNA fragments to well
lane with marker DNA fragments
1 prepare the gel
2 load the DNA samples
3 apply electric current
4 stain the gel

Figure 3 The four steps in the separation of DNA fragments by agarose gel electrophoresis

Step 2. Load DNA sample solutions, such as PCR products, into the wells of the gel, beside a well loaded with DNA "marker" fragments. A **molecular marker** is a DNA fragment of known size that is used to determine the lengths of unknown fragments by comparison. Multiple copies of many different-sized markers are run in a separate lane at the same time for comparison. The sizes of the fragments in the sample are determined by comparing their travelling distances to the travelling distances of the known molecular markers.

A special dye, called a loading dye, is added. The dye has two functions. First, because it is denser than the DNA, the dye keeps the DNA from floating out of the well. It sinks, along with the DNA, into the well. Second, the dye travels slightly faster than the fastest nucleotide fragments. The rate at which the dye is seen to move can be used to judge the pace of the electrophoresis process.

molecular marker a fragment of a known size that is run as a comparison standard for gel electrophoresis

Step 3. Apply an electric current to the gel. DNA fragments are negatively charged, so they migrate toward the positive pole. Shorter DNA fragments migrate faster than longer DNA fragments. When the electric current is stopped, fragments of equal length will have travelled equal distances. The result will be clusters of equal-sized fragments forming invisible bands within the gel.

Step 4. To be able to see the DNA fragments once the process is complete, stain the electrophoresis gel. **Ethidium bromide** is one compound that can be used to stain the gel. It inserts itself inside the DNA double-helical ladder structure (see Section 7.5, page 343, Figure 4). When the gel is viewed under a UV light, the bands of DNA are visible because the ethidium bromide glows, or fluoresces.

ethidium bromide a large molecule that resembles a base pair, which allows it to insert itself into DNA; used for staining electrophoresis gels

Using gel electrophoresis, researchers can compare the size of the DNA fragments from an unknown sample to the size of the DNA fragments from a known sample to reach conclusions about the identity of the unknown sample. These conclusions may include the identity of the tissues of an endangered species, such as the lake sturgeon, or the identity of the perpetrator of a crime or the father in a paternity test. Researchers may also extract a particular DNA fragment from the gel. The extracted fragment can be purified and analyzed to determine its exact base-pair sequence.

Sequencing DNA

The development of DNA technologies for analyzing genes has revolutionized experimental biology. **DNA sequencing** techniques (analyzing and determining the base sequences of DNA) have made it possible for researchers to analyze the base sequences of cloned genes and DNA fragments amplified by PCR. Having the complete sequence of a gene helps researchers understand how the gene functions. Using just the nucleotide sequence, they can identify mutations, locate regulatory sequences and gene sequences, and compare homologous genes of different species.

DNA sequencing a process in which the sequence of base pairs in a DNA strand is determined

Many scientists have worked to develop methods for sequencing DNA (Section 8.5). One efficient method is called the chain termination method. It was developed by Frederick Sanger at Cambridge University in the 1970s. It relies on the addition of a labelled dideoxynucleotide (ddNTP) to a growing DNA strand. This nucleotide, when incorporated into the DNA, prevents the binding of the next nucleotide, thus terminating the elongation of the newly synthesized DNA strand. The labels on the dideoxynucleotides are dyes that fluoresce and can be used to identify the specific base when exposed to laser light.

For the chain termination method in the laboratory, four reaction tubes are set up, each with many copies of normal deoxyribose nucleotides (dATP, dTTP, dGTP, and dCTP), multiple copies of the DNA to be sequenced, DNA polymerase, and a DNA primer. Only one of the labelled dideoxynucleotides (ddATP, ddTTP, ddGTP, or ddCTP) is added to each tube (**Figure 4**). This dideoxynucleotide is in a much smaller concentration than the normal nucleotide. One tube contains ddATP, another ddTTP, another ddGTP, and the final one ddCTP. Synthesis of a complementary chain produces DNA fragments of different sizes, each with their last nucleotide labelled.

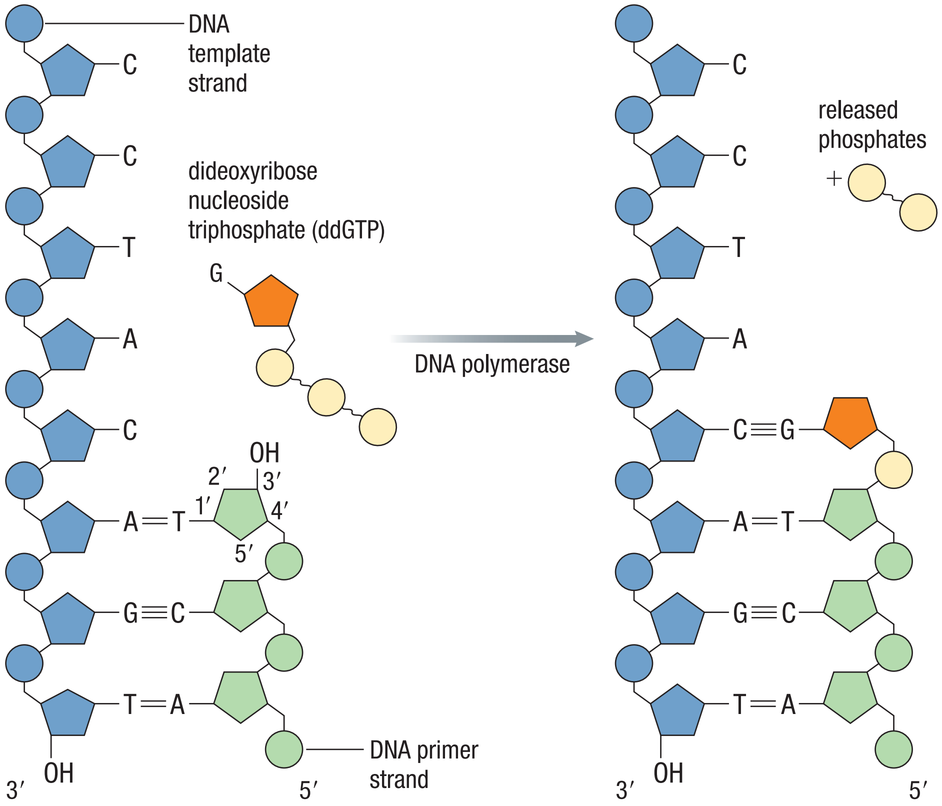


Figure 4 A complementary DNA strand can be terminated during Sanger Dideoxy sequencing. In the diagram on the right, synthesis of the DNA chain has terminated since there is no –OH group on the 3′ carbon for DNA polymerase to add another nucleotide.

The contents of the four reaction tubes are combined and then separated by gel electrophoresis with a resolution of only a single nucleotide. The sequence can then be determined by reading the order of the labelling type that corresponds to the specific dideoxynucleotide. This process is now computer automated (**Figure 5**, next page).

The entire human genome has now been sequenced, along with many other genomes. Many scientists worked on the project. They used two techniques, both involving the Sanger method for DNA sequencing. However, one technique, called the **whole-genome shotgun method**, proved to be faster than the other. This method was developed by Craig Venter of Celera Genomics. You will read more about Frederick Sanger and Craig Venter in Section 8.5.

whole-genome shotgun method a DNA sequencing method that involves blowing DNA strands into many fragments and then using computer technology to sequence and reassemble the fragments

In the shotgun method, many copies of the DNA are randomly cut into tiny fragments by passing the DNA through a pressurized syringe. The fragments are cloned in plasmids and then sequenced using the Sanger method. Computer software is used to determine the overall sequence by analyzing the many partial sequences (**Figure 6**, next page). The shotgun method is analogous to tearing 10 copies of a book randomly into smaller sets of a few pages each and, by matching overlapping pages, reassembling a complete copy of the book with the pages in the correct order.

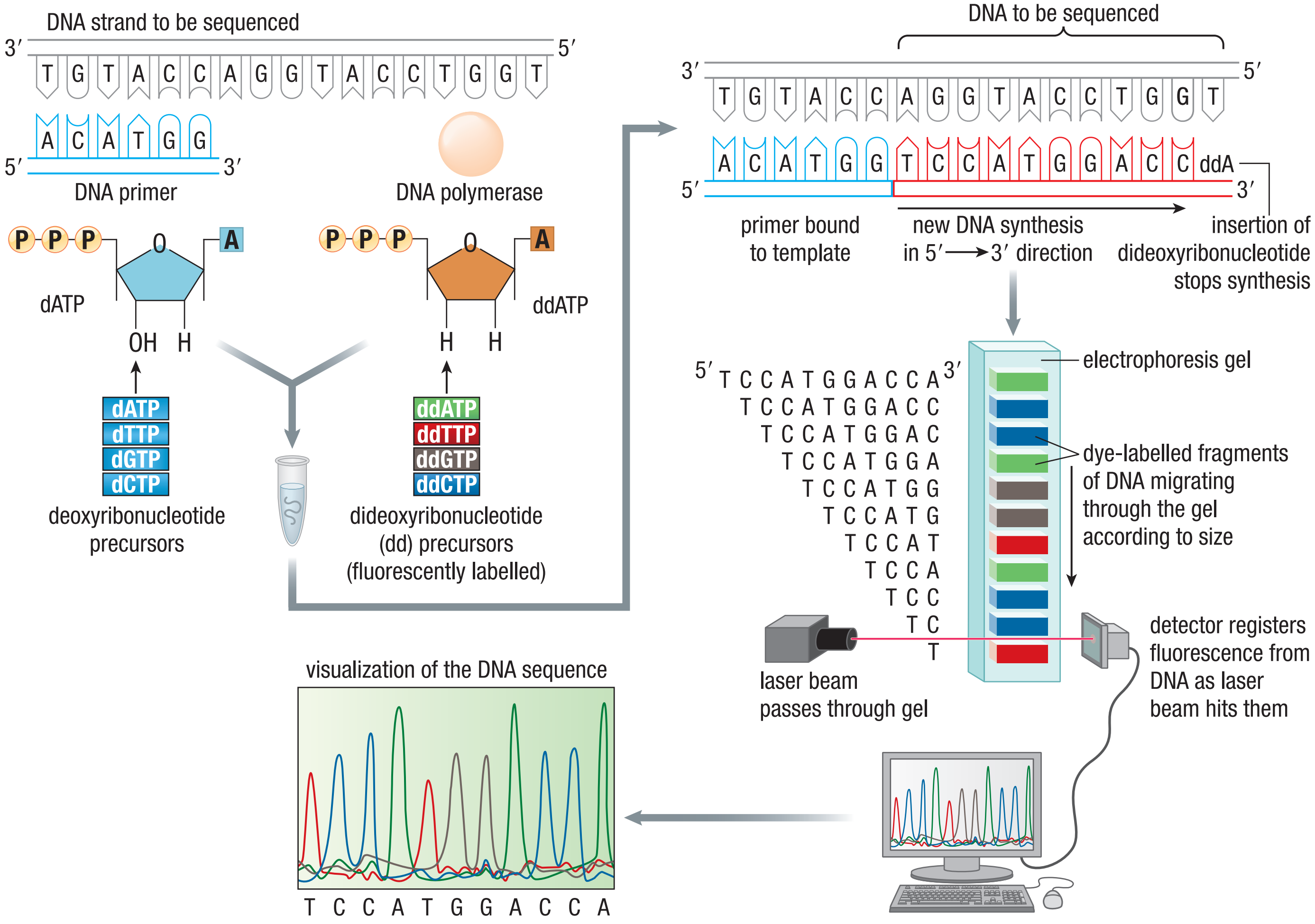

DNA strand to be sequenced
3′ T G T A C C A G G T A C C T G G T 5′
5′ A C A T G G 3′
DNA primer
DNA polymerase
P P P O A
dATP
OH H
P P P O A
ddATP
H H
dATP
dTTP
dGTP
dCTP
deoxyribonucleotide precursors
ddATP
ddTTP
ddGTP
ddCTP
dideoxyribonucleotide (dd) precursors (fluorescently labelled)
DNA to be sequenced
3′ T G T A C C A G G T A C C T G G T 5′
5′ A C A T G G T C C A T G G A C C ddA 3′
primer bound to template
new DNA synthesis in 5′⟶3′ direction
insertion of dideoxyribonucleotide stops synthesis
5′ T C C A T G G A C C A 3′
T C C A T G G A C C
T C C A T G G A C
T C C A T G G A
T C C A T G G
T C C A T G
T C C A T
T C C A
T C C
T C
T
electrophoresis gel
dye-labelled fragments of DNA migrating through the gel according to size
laser beam passes through gel
detector registers fluorescence from DNA as laser beam hits them
visualization of the DNA sequence
T C C A T G G A C C A

Figure 5 This diagram shows the chain termination (Sanger) method for sequencing DNA.

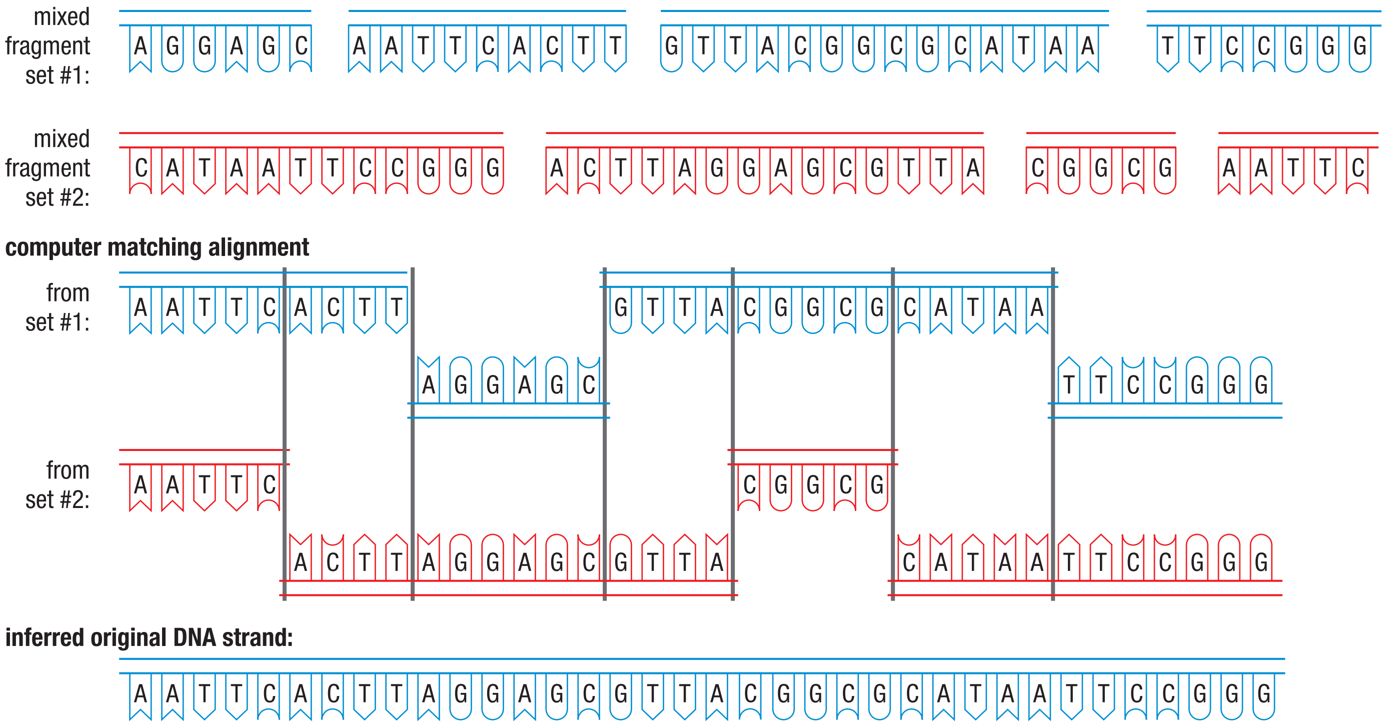

mixed fragment set #1:
A G G A G C
A A T T C A C T T
G T T A C G G C G C A T A A
T T C C G G G
mixed fragment set #2:
C A T A A T T C C G G G
A C T T A G G A G C G T T A
C G G C G
A A T T C
computer matching alignment
from set #1:
A A T T C A C T T
G T T A C G G C G C A T A A
A G G A G C
T T C C G G G
from set #2:
A A T T C
C G G C G
A C T T A G G A G C G T T A
C A T A A T T C C G G G
inferred original DNA strand:
A A T T C A C T T A G G A G C G T T A C G G C G C A T A A T T C C G G G

Figure 6 Note how the overlapping sequences of fragments (produced using the shotgun method) from the two sets can be used to infer the original sequence of the DNA molecule.

However, a drawback to the shotgun method was discovered. If the genome has repeating sections, it is difficult (or even impossible) for the computerized analysis to detect where these repeats are. This causes some errors in the results. Since the development of the shotgun method, however, advances in DNA sequencing technologies have allowed scientists to determine the sequences of genomes at a much faster rate.

Analyzing Genomes

Once the sequence of a whole genome has been derived, there are two approaches that can be used for its analysis: **structural genomics** (the study of the actual sequencing of genomes and the analysis of the nucleotide sequences to locate genes within the genome) and **functional genomics** (the study of the functions of genes, how they are expressed, what proteins they encode, and what role these proteins play in metabolic processes).

structural genomics the study of the structure of genes and their locations in a genome, as well as the analysis of the nucleotide sequences to locate genes within the genome

functional genomics the study of the functions of genes, the proteins they make, and how these proteins function

bioinformatics the use of computer technology to process a large amount of biological data

Most research is focused on functional genomics because genes control the functions of cells, and therefore the functions of organisms. Functional genomics relies on **bioinformatics**: the combination of laboratory experiments and sophisticated computer analyses. Bioinformatics can be used, for example, to find a gene within a genomic sequence, align sequences in databases to determine the degree of matching, predict the structure and function of a gene product, and postulate evolutionary relationships for sequences.

Genes that code for proteins are particularly interesting in genome analysis. Once a genome is sequenced, researchers use computer algorithms to search both strands of the sequence for these genes. A genome can be translated by the computer to give the amino acid sequence of the protein it could encode. Researchers may then be able to assign a function to the amino acid sequence by performing a sequence similarity search: a computer-based comparison of a DNA or amino acid sequence with databases of sequences of known genes or proteins. If the sequence resembles that of a previously sequenced gene, the two genes are related in an evolutionary sense and are likely to have similar functions.

Analysis of genome sequencing has led to many new discoveries about genetic organization, and many earlier hypotheses have been verified or disproven. A surprising discovery is that the eukaryotic genomes sequenced to date contain large numbers of previously unknown genes—many more than scientists expected to find. In *Caenorhabditis* (a nematode), for example, 12 000 of the 19 000 genes have no known function. Identifying these genes and their functions is one of the major challenges for molecular geneticists. Another surprising discovery is the degree to which different organisms, some widely separated in their evolution, contain similar genes. For example, even though the yeast *Saccharomyces*, a single-celled fungus, is separated from our species by hundreds of millions of years of evolutionary history, about 2300 of its approximately 6000 genes are related to mammalian genes. Many of these related genes control progress through the cell cycle. The similarities are so close that the yeast and human versions of several genes can be interchanged with little or no effect on cell functions in either organism.

Gene sequences also show that eukaryotic genomes contain large numbers of noncoding sequences, most of them in the form of repeated sequences of various lengths and numbers. Although these sequences make up about 25 to 50 % of the total genomic DNA in different eukaryotic species, their functions are unknown at this time.

Investigation **8.2.1**

Looking for *Wolbachia* (p. 400)
Now that you have learned about DNA sequencing, you can perform Investigation 8.2.1 and simulate DNA sequencing to research a host–parasite relationship.

Nanopore Sequencing

Nanopore sequencing is a revolutionary method that scientists have been working to perfect since 1995. It involves drawing individual strands of DNA through tiny submicroscopic holes called nanopores and reading the DNA sequence, one base pair at a time, as the strand passes through the nanopore. All of the DNA bases (A, C, T, and G) fit precisely through a 2.5 nm hole. Some transmembrane cellular proteins work well for nanopore sequencing, although a tiny hole drilled in a superthin sheet of silicon has also been used. Each base is detected as it passes through the pore by an ingenious way of reading the conduction of a current across the silicon sheet. The current that passes is slightly different, depending on which base is passing through the nanopore at the time (**Figure** 7).

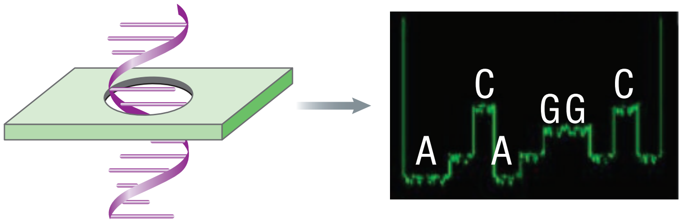


Figure 7 Nanopore sequencing may pave the way to inexpensive gene sequencing in the future.

The development of nanopore sequencing is one of many efforts by genetic technologists around the world to win the "$1000 genome initiative." The race is on to come up with a method that will allow any human to have his or her entire genome sequenced for a fee.

Studying Gene Function Using DNA Microarrays

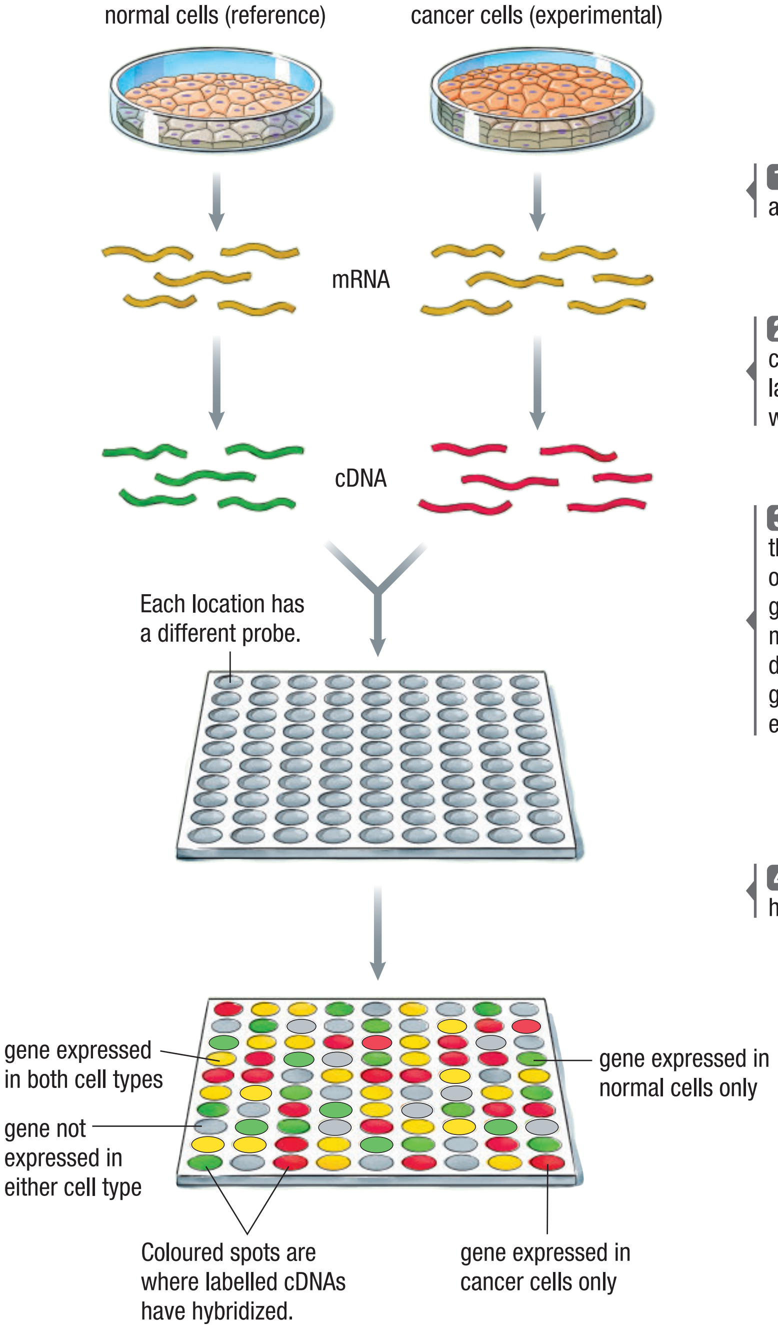
A **DNA microarray** is a technology that helps scientists pinpoint the functions of specific genes, rather than just their locations, and to compare the expressions of genes in different types of cells or different organisms. Microarrays can be used to understand the processes involved in the development of an organism or to detect genetic mutations by comparing an individual's DNA with so-called normal DNA.

DNA microarray a solid surface that has a microscopic grid of many DNA fragments, called probes, attached; used to determine gene expression

A microarray, or gene chip, is designed to hold many individual DNA samples, ranging from just 10 to 2.1 *million*. These DNA samples, called probes, are known sequences, and the location of each probe on the chip is also known. The technology that is used to create microarrays is similar to the technology that is used to lay out electronic circuits on a computer chip.

Figure 8 (next page) shows how microarray technology works. The microarray protocol starts with the isolation of mRNA from the two types of cells to be compared: a reference cell (a normal cell) and an experimental cell (such as a cancer cell). The extracted mRNA is used to build complementary DNA (cDNA) libraries. The cDNA from each type of cell is labelled with a specific dye, such as green dye for the reference cell and red dye for the experimental cell. The cDNA sequences are then denatured into single strands and placed onto the surface of the DNA microarray.

The DNA microarray contains probes that correspond to the coding genes of the genome being studied. Any labelled cDNA that is complementary to the sequence of a probe will bind (hybridize) to this probe, while cDNA with no matching sequence will be washed off the chip. The fluorescence is then detected, and its location is recorded. Green spots mean that the reference cDNA was hybridized with the probe; hence, the gene for the corresponding protein is expressed in the normal cell. Red spots mean that the experimental cDNA was hybridized with the probe; in other words, the gene was active in the experimental cell (the cancer cell). Yellow spots mean that cDNA for both the reference cell and the experimental cell were hybridized. Both the normal cell and the cancer cell express the same gene. Researchers can then determine which genes have altered expressions in the cancer cell. The advantage of the microarray is that the expressions of thousands of genes can be identified simultaneously in a particular cell.


normal cells (reference)
cancer cells (experimental)
mRNA
cDNA
Each location has a different probe.
gene expressed in both cell types
gene not expressed in either cell type
gene expressed in normal cells only
Coloured spots are where labelled cDNAs have hybridized.
gene expressed in cancer cells only

1 Isolate mRNAs from a control cell type (here, normal cells) and an experimental cell type (here, cancer cells).

2 Prepare cDNA libraries from each mRNA sample. For the control cell library, use nucleotides with a green fluorescent label, and for the experimental cell library, use nucleotides with a red fluorescent label.

3 Denature the cDNAs to single strands, mix them, and pump them across the surface of a DNA microarray containing a set of single-stranded probes representing every protein-coding gene in the human genome. The probes are attached to the microarray surface, with each location containing a probe for a different gene. Allow the labelled cDNAs to hybridize with the gene probes on the surface of the chip, and then wash excess cDNAs off.

4 Locate and quantify the fluorescence of the labels on the hybridized cDNAs with a laser detection system.

actual DNA microarray result

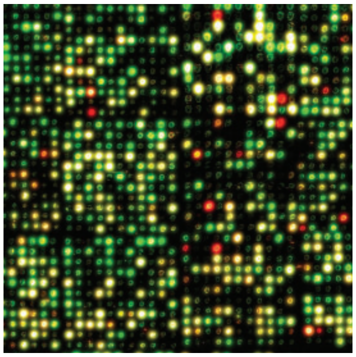


Figure 8 DNA microanalysis of gene expression levels

8.2 Review

Summary

- The polymerase chain reaction (PCR) is used to make many copies of short DNA sequences rapidly. This is useful for applications in which only a tiny sample is available, such as forensic applications.
- DNA fragments are separated by size using gel electrophoresis.
- Genomes are analyzed structurally to determine the DNA sequence. DNA sequences can be compared to detect mutations and also to study sequences that do not contain a gene but can have an important role.
- DNA sequencing can be done using the Sanger method (chain termination method) and the shotgun method.
- Genomes are analyzed to understand the function of each gene, the protein it codes for, and the function of the protein in the cell.
- Nanopore sequencing is a promising method that could be inexpensive, quick, and easy. It involves running a DNA strand through a tiny hole and measuring the current.
- DNA microarray technology can be used to detect mutations, study gene functions, and compare the expressions of genes in different tissues, individuals, and organisms.

Questions

1. Explain the role of each of the following in the PCR. K/U T/I
   (a) the DNA primer
   (b) the choice of Taq polymerase
   (c) the cycling through three different temperatures
2. Explain, using at least two or three details, how PCR technology has revolutionized genetic testing. What are the benefits for society? What are some possible disadvantages for society? K/U T/I
3. Why does the double-stranded DNA have to be raised to a temperature of 94 to 96 °C for denaturation to occur? T/I
4. PCR requires the use of two DNA primers: one complementary to the 3′ region of the target area on one strand, and the other complementary to the 3′ region of the target area on the opposing strand. Why must two different primers be used? T/I
5. How can materials as simple as agarose gel, an electric field, and a DNA stain be used to separate and compare different fragments of DNA? K/U
6. How and when is gel electrophoresis used in general society? K/U
7. A plasmid was digested using restriction enzymes. The following DNA fragments were produced: 1200 bp, 1800 bp, 200 bp, and 750 bp. T/I C
   (a) Which fragment will travel the fastest in an agarose gel? Why?
   (b) Which fragment will travel the slowest in an agarose gel? Why?
   (c) Sketch the gel pattern that would result after running this plasmid digestion in an agarose gel.
8. Compare and contrast the Sanger method and the shotgun method of DNA sequencing. How is a computer used in each method? K/U
9. Compare and contrast structural and functional genomics. K/U T/I
10. What benefits do microarrays add to the variety of genetic technologies at our disposal? K/U
11. The genomes of several species, such as *Caenorhabditis*, *Saccharomyces*, and *Drosophila*, were sequenced about the same time as the human genome was sequenced. Why do you think the choices of these organisms did, or did not, make sense? Share your reasons with a partner. T/I C

8.3 Genetic Engineering: Redesigning Life

For centuries, people have bred plants and animals to get the best characteristics in the progeny. Before Mendel's pea experiments, people mated a prolific egg-laying hen with a strong rooster, a good milk-producing cow with a closely related bull, and a large flower with a colourful flower. They saved and replanted the grains of the best-yielding wheat. Their efforts resulted in the varieties of livestock, vegetables, flowers, and field crops that we see today.

Farmers now tend to grow the varieties that are easiest to grow, store, and ship; that are resistant to pests; and that give the best yields under their environmental conditions. As a result, some varieties of agricultural plants and animals are no longer planted or raised—they are no longer good economic choices for farmers. However, in Canada and other countries, there is now a movement to raise and protect these "heirloom varieties." An heirloom variety is a variety of a species that was grown for a long time but is no longer commercially produced. For example, gardeners raise heirloom tomatoes (**Figure 1**), and hobby farmers raise endangered horse populations. Maintaining production of these varieties preserves the genetic diversity of their species. If a disease suddenly wipes out cabbage crops, for example, one or more of the heritage varieties might be resistant to this disease. Agronomists would propagate these plants and breed them with other cabbage plants to give their disease resistance to all cabbage plants. Alternatively, agronomists might extract the gene for disease resistance from the healthy plants and insert it into other cabbage plants.

Figure 1 Heirloom tomatoes can be quite different from the tomatoes you usually see in stores.

Biopharming

Genetic engineering uses DNA technology to modify the genes of a cell or an organism. Molecular biologists can introduce new functions into an organism. An early demonstration of genetic engineering is the glowing tobacco plant shown in **Figure 2**. Today, scientists use genetic engineering to find cures for various diseases that affect animals and plants. Perhaps most useful is the introduction of one or more genes from one organism into another. This could cause the host organism to produce a certain protein, such as insulin, that is useful to us. When such pharmaceutical products are produced on a large scale, the process is called **biopharming**.

Some biopharming methods involve the genetic engineering of organisms to produce a target protein. For example, cattle have been genetically engineered to produce a target protein in their milk, and safflower plants have been genetically engineered to produce such a protein in their seeds. Some genetically modified goats are able to produce spider silk proteins in their milk. These proteins can be removed from the milk and used in manufacturing. The genetic change is engineered in the germ line of the species, and the ability to make the new protein is passed on to the offspring of the original genetically engineered goat. Thus, there can be an entire herd of biopharming dairy goats! Medically important proteins, such as the life-saving anticoagulant antithrombin, can be produced quite inexpensively by genetic engineering, compared with using laboratory techniques.

Although this biotechnology is promising, it should be approached with caution. Even a minor change in an animal's genome may prove to have negative consequences in the future, such as to an animal's long-term health.

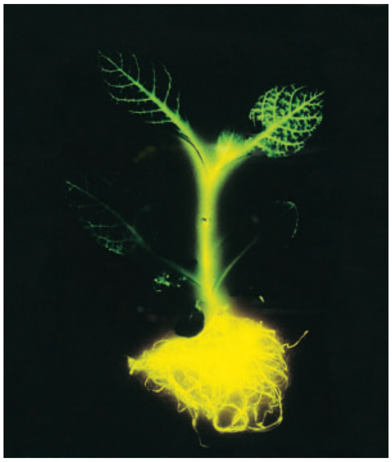


Figure 2 Genetic engineering can produce some very wild results. This tobacco plant glows because a firefly gene, which encodes for the enzyme luciferase, has been inserted into its DNA.

biopharming a process in which genetically engineered host organisms are used to make pharmaceuticals or other products that are useful to humans

Transgenic Organisms: Altered DNA

An organism that has been changed by scientists to contain one or more genes from another organism is known as a **transgenic organism** or a **genetically modified organism (GMO)**. The *E. coli* bacteria that were altered to become insulin factories are an example of a GMO.

transgenic organism (genetically modified organism, GMO) an organism that has been modified to carry genes it does not normally carry

More recent developments in insulin production may be even cheaper and faster than the bacterial methods discussed earlier. For example, genetic engineers at the University of Calgary have discovered how to get safflowers to produce insulin. The DNA is easily manipulated, and the desired product(s) can be harvested in the oil from the seeds. Safflower is an easily grown thistle-like plant that prefers arid conditions (**Figure 3**). Maurice Moloney was one of the scientists behind the genetic engineering of safflower-produced insulin. At an agricultural biotechnology conference in Saskatoon, Saskatchewan, he explained how plants could be used to produce a biodegradable plastic called polyhydroxybutyrate (PHB): WEB LINK

> *PHB is a biopolymer produced in certain bacteria. PHB production requires the intervention of three enzymes. Plants lack these enzymes, but the bacterial genes specifying these biochemical conversions have been expressed in plants. The result is that a significant amount of carbon metabolism is re-routed into the production of PHB.*
>
> *One of the main factors limiting the wide use of PHB polymers as an environmentally benign plastic is the cost of production in microorganisms. Production in plants could address this problem and render PHB an economically viable material for production of milk containers, plastic bags, and a variety of disposable packaging.*

Figure 3 A safflower, the plant from which genetic engineers are now harvesting insulin

Why Use Transgenic Plants and Animals?

Why did scientists not stick with bacteria to produce insulin and other genetically engineered products? Why have they researched the use of goats and plants as protein factories? One reason for the expanding research is cost. Animal- and plant-based methods are usually more economical than operating a laboratory with controlled bacterial populations. As a result, the cheaper insulin from safflowers, for example, could improve the lives of diabetics in the developing world, where many people cannot afford insulin at the current prices. Since 5 % of deaths worldwide are attributed to diabetes, the production and availability of less expensive insulin is an important goal.

A second reason why plants and animals may be better to use than bacteria is that larger organisms can produce larger molecules. Transgenic goats can produce larger proteins, with more complex folding patterns, than bacteria can. Other transgenic organisms are engineered to be bigger and/or better versions of themselves, which is usually considered to be a benefit commercially (**Table 1**). Many other organisms are still being developed (**Table 2**). CAREER LINK

Table 1 GMOs Commercially Available in Canada and Their Benefits

Genetically modified organism	Benefit
coho salmon	faster maturation
cattle	resistance to mad cow disease
tomatoes	better travel durability between field, store, and table; better flavour
canola	resistant to herbicides and pests; altered fatty acid composition
corn	resistance to pests
soybeans	herbicide tolerance (so that weeds can be sprayed without affecting the soybean plants)

Table 2 Some GMOs Currently under Research

Organism	Benefit
rice	better vitamin content (specifically, betacarotene)
tobacco	hepatitis B vaccine
corn	oral vaccines

Transgenic Plants

Genetically modified (GM) canola and other field crops have been engineered to be resistant to specific herbicides. This technology means that herbicides can be sprayed to kill weeds but the crop plant remains healthy. The oil from the genetically modified canola plant is identical to conventional canola seed oil. Approximately 80 % of the western Canada canola crop is the genetically modified variety. Farmers spend about 40 % less on herbicides for GM canola crops, versus conventional canola crops, and they report up to a 10 % increase in yield.

An advantage of GM plants is their potential to provide food for millions of hungry people in the developing world. A major drawback of GMOs is the increased cost of the patented seeds, making them unaffordable to some farmers. For a family in the developing world, however, having higher-yielding and pest-resistant crops might mean the difference between hunger and a better life.

Knockout Mice

Knockout mice are produced by genetic engineering to have at least one gene completely turned off by a mutation. They are used to study the purpose of each gene and to draw parallels to humans. Knockout mice have been very useful in learning about the effects of certain genes on human health, since the mouse genome is quite similar to the human genome.

Knockout mice are not actually “knocked out.” They are simply homozygous for one particular gene. Both copies of this gene are altered to a non-functional state so that scientists can study the effects on a mouse without it. Sometimes, an alteration does not seem to cause any change in the structure or function of the mouse. Other times, a loss of gene function significantly changes the phenotype. For example, in one mouse, scientists knocked out the p53 gene, which helps to stop tumour growth. Scientists have discovered that humans are more likely to get certain cancers if they have a mutation in this gene. The p53 knockout mice got cancers, but not in exactly the same tissues as humans with the mutation do. Much useful research is accomplished with this method, even though the expression of the genes may vary.

Societal Concerns and Implications

If you could save lives by producing vaccines in transgenic bananas, would you? Deciding exactly where to draw the line on transgenic organisms is difficult. There is no doubt that there are many benefits, but what about the risks? Because of the potential ramifications of GMOs, societies and governments are moving cautiously.

Genetic engineering is a new biotechnology, and, as a result, many people, including scientists, are concerned that there may be far-reaching irreversible effects. For example, a genetically modified organism such as GM canola might outcompete native or non-modified species. Being resistant to herbicides, the organism could become a weed itself. None of this has yet been proven, but some governments, including the Canadian government and several in the European Union, are concerned.

Competition is not the only concern. People are also asking whether crops or animals that produce medical products might interbreed with native plants or animals. The proximity of GMO farms to traditional and organic farms is a concern because of potential cross-pollination and contamination. Another concern is that GM plants might contain toxins and harm any animals that eat them. Some medicine-producing safflowers, for example, are poisonous.

Intense herbicide application on herbicide-resistant GM crops is a concern due to potential soil and water contamination. This could be especially problematic for drinking water supplies and organisms living in nearby lakes and streams. GMOs are often advertised as reducing the need for pesticides. However, it is difficult to make general statements given that each plant species reacts differently under different conditions.

Transgenic fish in aquaculture tanks have escaped and mixed with wild species in the ecosystem. While the transgenic fish had mating advantages over the wild species, the offspring of the transgenic fish were not as viable as the wild fish offspring. Thus, the transgenic fish reduced the population of the fish species overall.

Regulations vary a great deal, depending on the country developing the GMOs. North America and Europe have a rigorous testing and approval process, and crops are often not released for up to 10 years. In contrast, China's government allows the immediate release of some GM crops. This could have huge implications for environmental protection if adequate testing is not required prior to implementation in the field.

A further concern is related more to politics and society than to science: Should the inventors of the technology be allowed to reap a profit indefinitely? If so, at what cost to the environment or the public? A main concern with genetically modified seeds is the power given to patent holders. Farmers are not allowed to save seeds from their crop for the next year because the companies with the patents want them to buy new seeds. Should this kind of policing of patents be allowed, or should the patent laws be changed to make GMO technology more public? To date, extensive lawsuits over patented seeds have been filed by GMO companies that have strict contracts with farmers.

Consumer groups would like to see the Canadian Food Inspection Agency change labelling rules so that consumers can decide for themselves whether they want to buy a product that contains a GMO.

The applications of genetic engineering already include biofuel production, food processing, sewage treatment, drug development, and pollution control. What else will the future bring?

Research This

Analyzing Concerns about GMOs

Skills: Questioning, Researching, Analyzing, Evaluating, Communicating, Defining the Issue, Defending the Decision

SKILLS HANDBOOK **A4.1, A4.2**

As discussed in this section, GMOs are increasingly being used for medical applications and food supplies. However, there are many concerns with GMOs.

1. Choose a GMO from Table 1 or 2 on page 387 or another GMO that interests you. Research this GMO, its applications, its benefits, and any concerns for society and the environment.

A. Are the concerns about the application of this GMO valid? Provide reasons for your decision. Your reasons may include societal, cultural, economic, political, and environmental implications. T/I

B. Even with the potential concerns, do you believe that the GMO should continue to be used? Provide reasons for your decision. T/I

C. From the viewpoint of a government scientist, write a summary for the Ministry of the Environment about the pros and cons of the GMO. Include your recommendations for the use of this technology. T/I C

WEB LINK

8.3 Review

Summary

- Genetic engineering produces transgenic, or genetically modified, organisms (GMOs) by inserting DNA from one species into another species.
- GMOs offer many benefits for humans, such as higher crop yields and lower dependence on herbicides and pesticides.
- Plants and animals, rather than bacteria, are often used in genetic engineering because they are more economical to maintain and they can produce larger molecules.
- Because genetic engineering is a new biotechnology, many people are concerned that there may be far-reaching, irreversibly harmful effects.

Questions

1. What are heirloom varieties of plants or animals? Why is it important that they be preserved? K/U
2. List the potential benefits of biopharming for developing countries. T/I
3. What is a transgenic organism? List at least three plant species and two animal species that have been genetically modified, as well as the purpose for each modification. K/U
4. Transgenic goats are very different from transgenic bacteria. Why would scientists choose to develop a transgenic goat, not a transgenic bacterium, to produce a protein? K/U
5. What is a knockout mouse? What are some benefits of using knockout mice in scientific research? K/U
6. List some concerns that people have with transgenic organisms. List some personal concerns. K/U T/I C
7. Look at Tables 1 and 2 on page 387. Do you support these initiatives? Explain why or why not. T/I C
8. Currently there is a big push from environmentalists and the public to include information about any genetically modified organisms used in our food. Use a t-chart to identify the pros and cons of including GMO information on food labels. T/I C
9. Research the role of the Canadian Food Inspection Agency with respect to genetic engineering. What does this agency do? How much power does it have in steering the direction of food science research in Canada? 🌐 T/I C
10. Choose one GMO, and research the benefits and risks associated with it. Summarize your findings, and then give your opinion about whether this is a good technology to pursue. 🌐 T/I C A
11. In Canadian patent law regarding biopharming, the legislation prevents patenting "higher" genetically modified organisms. Using the Internet, research how Canadian law defines a "higher organism" and how the Supreme Court has ruled on patenting GMOs in Canada. 🌐 T/I
12. Suppose you are a researcher at Agriculture and Agri-Food Canada and you want to remove the gene that prevents fish from freezing in sub-zero temperatures and place it in a tobacco plant. Your goal is to have the plant produce the "antifreeze" protein to protect it from frost. K/U T/I C
    (a) Draw a flow chart that summarizes the steps in this genetic technology.
    (b) Discuss the economic advantage of this technology for tobacco farmers.
    (c) Suggest one ethical issue that may arise from this technology.

🌐 WEB LINK

Biotechnology and Health

8.4

The science of genetics is revolutionizing the way that doctors treat diseases. Although many older treatment methods are still more effective, a large number of hereditary diseases have now been identified and can be treated because of genetic studies.

Some treatments involve a specific diet. For example, phenylketonuria (PKU) is a hereditary disease that causes a buildup of the amino acid phenylalanine in the body. If PKU is not treated, phenylalanine accumulates and can damage the brain tissue. This results in developmental defects, intellectual disabilities, and seizures. Fortunately, PKU is easily diagnosed in a newborn baby, using a blood sample obtained by pricking the baby's heel (**Figure 1**). Children with PKU are kept on a strictly controlled diet during childhood and adolescence. Although adults have lesser symptoms of PKU, they still remain on a diet low in phenylalanine. Another disease, familial hypercholesterolemia, is linked to high levels of "bad," low-density lipoprotein (LDL) cholesterol and early heart disease. It is controlled by dietary modifications and the administration of a class of drugs called statins. WEB LINK

Figure 1 All newborn babies in Canada are tested for PKU.

Some inherited diseases are treated by directly providing the proteins that are missing due to defective genes. Clotting proteins are injected to treat hemophilia, and digestive enzymes are taken orally to treat digestive disorders and cystic fibrosis (CF). CF results in the accumulation of thick mucus in the lungs, digestive tract, and pancreatic ducts. The mucus prevents pancreatic enzymes from reaching the intestines. Pancreatic enzyme replacement can be administrated to aid with digestion and the absorption of food.

Surgical solutions to hereditary disorders might include repairing a defective organ or replacing it with a transplant. For example, Alpha-1 antitrypsin deficiency (AATD) can cause liver deficiency. It is the most common reason for liver transplants in children.

New gene therapies offer many innovative ways to address genetic diseases. Rather than allowing a disease to affect the body and then trying to fix the symptoms, **gene therapy** gets to the source of the disease—the mutated DNA sequence itself—by replacing, removing, or altering the defective gene before the symptoms are expressed.

gene therapy the insertion, removal, or replacement of genes (to correct defective genes) within an organism's cells to treat a disease

Gene Therapy: Correcting Genetic Disorders

Gene therapy began with experiments using mice. In 1982, Richard Palmiter of the University of Washington, Ralph Brinster of the University of Pennsylvania, and their colleagues injected a growth hormone gene from rats into fertilized mouse eggs and then implanted the eggs into a surrogate mother (**Figure 2**, next page). The mother gave birth to normal-sized mouse pups, but some grew faster than normal, to about twice the size of their littermates. These giant mice attracted extensive media attention from around the world.

Palmiter and Brinster next attempted to cure a genetic growth hormone deficiency by gene therapy. They introduced a normal copy of the growth hormone gene into fertilized eggs taken from mutant dwarf mice and then implanted the eggs into surrogate mothers. The transgenic mouse pups grew to slightly larger than normal, demonstrating that the genetic defect in these mice had been corrected.

This type of experiment, in which a gene is introduced into the germ-line cells (sperm cells or eggs) of an animal to correct a genetic disorder, is called **germ-line gene therapy**. The changes made by germ-line gene therapy may be passed on to future generations. For ethical reasons, germ-line gene therapy is not permitted with humans. Instead, humans are treated with **somatic gene therapy**, in which genes are introduced into somatic cells (any body cells but germ cells). Any modifications and effects of somatic gene therapy will be restricted to the individual and will not be inherited by offspring.

The first successful use of somatic gene therapy with a human subject was carried out in the 1990s by W. French Anderson and his colleagues at the National Institutes

germ-line gene therapy a process in which germ cells (sperm cells or eggs) are modified by integrating functional genes into their genomes

somatic gene therapy a process in which therapeutic genes are transferred into somatic cells to treat a genetic disease

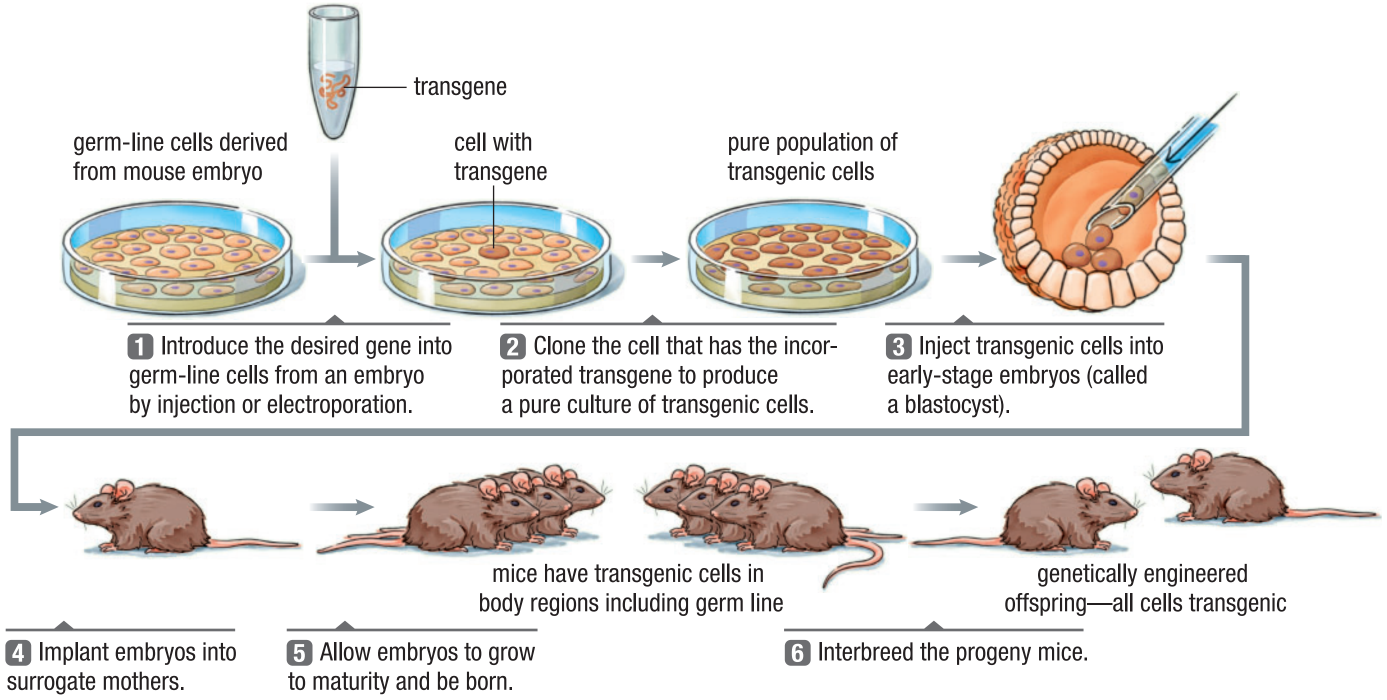

transgene
germ-line cells derived from mouse embryo
cell with transgene
pure population of transgenic cells
1 Introduce the desired gene into germ-line cells from an embryo by injection or electroporation.
2 Clone the cell that has the incorporated transgene to produce a pure culture of transgenic cells.
3 Inject transgenic cells into early-stage embryos (called a blastocyst).
mice have transgenic cells in body regions including germ line
genetically engineered offspring—all cells transgenic
4 Implant embryos into surrogate mothers.
5 Allow embryos to grow to maturity and be born.
6 Interbreed the progeny mice.

Figure 2 The introduction of genes into mouse embryos using embryonic germ-line cells

of Health (NIH) in Bethesda, Maryland. The subject was a young girl with a genetic disorder called adenosine deaminase deficiency (ADA). Without the adenosine deaminase enzyme, white blood cells cannot mature. As a result, the body's immune response is so poor that most children with ADA die of infections before reaching puberty. The researchers successfully introduced a functional ADA gene into mature white blood cells that had been isolated from the girl. These cells were then reintroduced into the girl, and expression of the ADA gene provided a temporary cure for her ADA deficiency. The cure was not permanent because mature white blood cells, produced by the differentiation of stem cells in the bone marrow, are non-dividing cells with a finite lifetime. Therefore, the somatic gene therapy procedure has to be repeated every few months. The subject in this example still receives periodic gene therapy to maintain the necessary levels of the ADA enzyme in her blood. In addition, she receives direct doses of the normal enzyme. CAREER LINK

Successful somatic gene therapy has also been achieved for sickle-cell disease. In December 1998, the bone marrow cells (the source of blood cells) of a 13-year-old boy were replaced with stem cells from the umbilical cord of an unrelated infant. The hope was that the stem cells would produce healthy bone marrow cells. The procedure worked, and the patient was declared cured of the disease.

Despite enormous efforts, human somatic gene therapy has not been the panacea that people expected. Relatively little progress has been made since the first gene therapy clinical trial for ADA deficiency, described above. In fact, there have been major setbacks. In 1999, for example, a teenage patient in a somatic gene therapy trial died as a result of a severe immune response to the viral vector being used to introduce a normal gene to correct his genetic deficiency. Furthermore, some children in gene therapy trials that use retrovirus vectors to introduce genes into blood stem cells have developed a leukemia-like condition. Thus, somatic gene therapy is not yet an effective treatment for most human genetic diseases. It has occasionally been successful, however, for correcting models of human genetic disorders in experimental mammals. Although no commercial human gene therapy product has been approved for use, research and clinical trials continue as scientists try to combat genetic diseases. Some diseases, such as muscular dystrophy and cystic fibrosis, are debilitating; others may cause intelligence deficiencies, such as learning disorders; but a few, such as diabetes, are treatable.

Genetic Screening

Some genetic mutations are known to be associated with specific genetic disorders. **Genetic screening** uses biochemical and molecular tests to detect these mutations. In some cases, early genetic screening means that treatment or therapy can be started before the disease fully takes hold in the body. For example, Huntington's chorea is a neurodegenerative disorder that usually does not affect people until after they have had children. People who know that this disease exists in their family can choose to have a genetic screening test to help them decide if they want to have children of their own or if they want to adopt instead. However, since Huntington's chorea is such a severe disease, knowing that you have it could be emotionally damaging. Do you really want to know, or do you not? Should you know?

genetic screening biochemical or molecular tests that are used to identify inherited disorders in parents, potential parents, embryos, or children after they are born

Doctors may recommend that some pregnant women, especially older ones, whose risk of mutations in the germ cell DNA is higher, have **amniocentesis**. Amniocentesis is a prenatal test that detects whether a baby carries chromosomal abnormalities such as trisomy 21 (which can indicate Down syndrome), trisomy 18 (which can indicate Edwards syndrome), or monosomy X (which can indicate Turner syndrome). With this knowledge, parents can better prepare for the arrival of a child with developmental challenges. Tests are also available for phenylketonuria, cystic fibrosis, and Duchenne's muscular dystrophy.

amniocentesis a genetic sampling method for testing *in utero*

Research This

Evaluating the implications of Gene Therapy

Skills: Researching, Evaluating, Communicating, Defining the Issue, Identifying Alternatives, Defending a Decision

SKILLS HANDBOOK **A4.1, A4.2**

Gene therapy is a technology in its infancy. Although gene therapy has had some promising results, it has also had some devastating setbacks, such as the death of test subjects. In the future, society will have to make choices about the use of gene therapy to treat disorders or diseases. What risks are we willing to take? Under what circumstances or conditions should gene therapy be used?

1. Using the Internet and other sources, research and distinguish between the three types of gene therapy: gene insertion, gene modification, and gene surgery.

A. Answer the following questions. T/I
   - Describe how each type of gene therapy works.
   - In your opinion, what are some of the arguments for and against gene therapy?
   - Describe some ways in which genes can be inserted into a genome to correct a defective gene.
   - Differentiate between somatic gene therapy and germ-line gene therapy.
   - What are some challenges that scientists have faced with gene therapy research?

B. Propose a set of guidelines to direct the future of gene therapy research. Consider the following criteria when developing your guidelines:
   - what the risk is to the population
   - who has access
   - what constitutes a "disease"
   - which type of gene therapy is worth the most research money T/I

C. In your opinion, do the risks of gene therapy outweigh the benefits? Comment using your guidelines and other research as supporting evidence. Summarize your argument in one page. Make sure that you account for ethical considerations in your argument. T/I C

WEB LINK

8.4 Review

Summary

- Genetic therapy involves replacing, removing, inserting, or repairing defective genes with genes that function properly.
- Somatic gene therapy improves the functioning of an individual's body cells, but the changes are not passed on to any offspring.
- Germ-line gene therapy involves sperm cells and eggs, so changes in an individual's DNA are passed on to the offspring.
- Genetic screening consists of biochemical or molecular tests to identify inherited disorders in people.

Questions

1. In your own words, define gene therapy. K/U
2. Create a graphic organizer to compare and contrast somatic gene therapy and germ-line gene therapy. K/U C
3. Does genetic screening help people? Consider both the pros and cons of genetic screening in your answer. K/U T/I
4. Explain how changing the diet of someone with phenylketonuria helps, and what change is made. K/U
5. What is amniocentesis? Why is it more likely to be recommended for older parents? K/U
6. What are other possible ways to treat genetic defects, besides gene therapy? K/U
7. Palmiter and Brinster devised germ-line gene therapy. Without checking Internet sources, develop a procedure that could possibly be used in germ-line gene therapy. K/U T/I
8. Describe how somatic gene therapy has been successful in combatting sickle-cell disease but has failed in other applications. K/U T/I
9. How are patients with the following diseases treated? K/U
   (a) ADA defect
   (b) sickle-cell disease
10. As shown by the example of insulin in this chapter, genetic engineering has many advantages. Gene therapy has saved innumerable lives. Research some other illnesses that gene therapy may provide solutions for in the future. T/I
11. Using the Internet and other sources, research one of the latest advances in gene therapy. Present your findings as a report or a poster. T/I C

WEB LINK

8.5 Biology JOURNAL

Sequencing the Human Genome: The Role of Collaboration and Competition in Science

SKILLS HANDBOOK A3

ABSTRACT

In 1990, the U.S.-funded, internationally supported Human Genome Project (HGP) was set up to map the human genome. The HGP team, led by Dr. Francis Collins, used the Sanger chain termination sequencing technique, beginning with a map of genetic landmarks on each chromosome. In 1998, however, their effort was challenged by a private company, Celera Genomics, led by Dr. Craig Venter. The Celera team proposed to decode the genome using the shotgun technique and intended to complete their work in just three years, four years ahead of the HGP target. This competition inspired the HGP team to accelerate their work. Both teams published their first working drafts of the human genome ahead of schedule, in February 2001.

In the early 1970s, scientists began to be able to read the base sequences of DNA and RNA. In 1977, Dr. Frederick Sanger and his co-workers developed the most reliable and easiest method at the time, called the chain termination method or the Sanger-dideoxy method (Section 8.2). About 10 years later, an automated sequencer was developed, initiating the idea of sequencing the entire human genome. However, sequencing took a huge amount of time; for example, it took a whole year just to get 1000 letters of genetic code.

Sequencing the Human Genome

In 1990, the U.S. Congress created and funded an international collaborative research program called the Human Genome Project (HGP), under Dr. Francis Collins. To quote an HGP team member,

> *…the challenge was to get a complete list of our As, Ts, Cs, and Gs … so the business of making tests, medicines, and cures could begin.*

The HGP team used the Sanger method.

Frustrated by the slowness of the project, Dr. Craig Venter left his position on the HGP in 1998. He founded his own company, Celera Genomics, with the goal of sequencing the entire genome in only three years. “Celera” comes from the Latin word for “speed.” Venter set a bank of computers running 24 h a day, every day, and used the shotgun technique that had been developed over the previous 20 years (Section 8.2).

The shotgun technique involved chopping human DNA into tiny pieces, which were copied repeatedly in bacteria and then tagged with coloured dyes. New analyzing equipment could read each colour one by one (**Figure 1**). Since each colour represented one of the bases on the genetic code, the sequences added up rapidly. After each fragment of DNA was sequenced, the computer added it to a layered pile. The position of each fragment in the pile was determined by how its sequence matched all the other sequences in the pile (Figure 6, page 381, in Section 8.2). Some scientists, however, thought that this shotgun technique was not as accurate as the Sanger method used by the HGP.

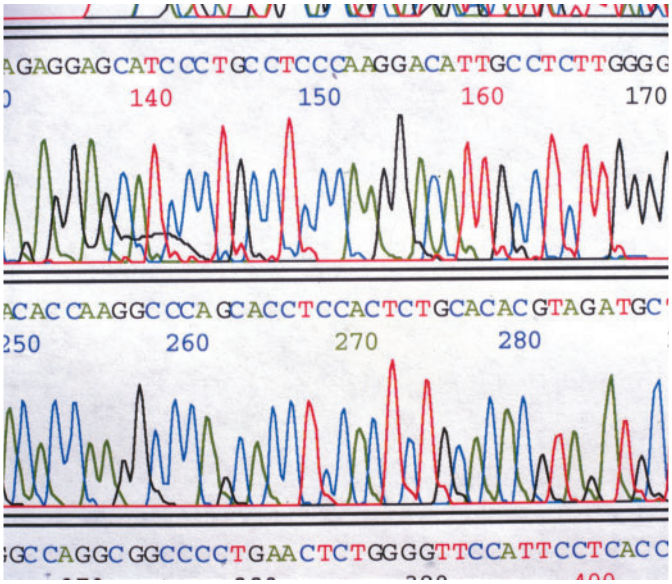


Figure 1 The process of reading the human genome is computer automated.

The Race

To quote Dr. Venter,

> *If you have two labs remotely working on the same thing, one tries to get there faster, or better, higher quality, something different, in part because our society recognizes only first place.*

Venter knew that whoever published the complete human genome first would be famous—front-page news, interviews with television journalists and talk-show hosts, just like celebrities. With two teams in the game, the project had become a race.

The publicly funded HGP team was now faced with the prospect of being beaten by a private company. Dr. Eric Lander, a prominent member of the HGP and a professor at the Massachusetts Institute of Technology (MIT), called the other leaders of the HGP together. If they wanted to finish the genome before Celera did, they would have to purchase new and unfamiliar equipment and step up their production rate.

Competition

Dr. Venter showed an entrepreneurial characteristic of science—competition. Helped by his tenacious nature, Venter did not give up on his project when he could not get funding via traditional channels. Instead, he raised his own money.

When discussing the HGP later, Dr. Lander acknowledged that even among academic groups there is still a lot of competition to be the first to publish scientific results. Competition pushes people both within and between organizations.

As a private company, Celera intended to patent the information and sell it to anyone who wanted it. The HGP, on the other hand, intended to publish the genome sequence so that it would be available, free of charge, to scientists around the world. Dr. Lander said later,

> *…we really felt deeply that these were data that had to be available for everybody. And there was an attempt to claim the public imagination for the proposition that these data were better done in some private fashion and owned.*

After the HGP geared up with their new equipment and techniques, both teams appeared to be running neck and neck. By June 2000, the HGP and Celera called it a tie. Dr. Collins said,

> *I think both Craig [Venter] and I were really tired of the way in which the representations had played out and wanted to see that sort of put behind us. It was probably not good for Celera as a business to have this image of being sort of always in contention with the public project. It certainly wasn't good for the public project to be seen as battling with a private sector enterprise.*

Both Venter and Lander published their work in February 2001, three years earlier than the HGP originally estimated (Lander et al., 2001; Venter et al., 2001). Since then, the shotgun method of sequencing DNA has become the standard method.

The Winner's Circle

In June 2000, Dr. Craig Venter and Dr. Francis Collins were both invited to the White House in Washington, D.C. In the presence of U.S. President Clinton and British Prime Minister Tony Blair, the two shook hands and announced the end of the project. In his speech, President Clinton said,

> *Nearly two centuries ago, in this room, on this floor, Thomas Jefferson … spread out a magnificent map [of a] courageous expedition across the American frontier all the way to the Pacific. Today the world is joining us here in the East Room to behold a map of even greater significance. We are here to celebrate the completion of the first survey of the entire human genome. Without a doubt this is the most important, most wondrous map ever produced by humankind.*

Competition drove the two projects by the two teams. In the end, however, everyone has benefited.

Further Reading

Lander, E.S., Linton, L.M., Birren, B., et al., (2001). Initial sequencing and analysis of the human genome. *Nature*, *409*, 860–921.

Marris, E. (2005). Free genome databases finally defeat Celera. *Nature*, *435*, 6.

Venter, J.C., Adams, M.D., Myers, E.W., et al. (2001). The sequence of the human genome. *Science*, *291*(5507), 1304–1351.

WEB LINK

8.5 Questions

1. What role did computer technology play in deciphering the human genome? K/U T/I
2. Using a graphic organizer, compare and contrast the research, methods, and attitudes of the HGP and Celera. K/U T/I C
3. Given the rate at which technology is changing, how would you plan a long-term project, such as the HGP? K/U
4. The process of science can be collaborative, competitive, driven by technology, or held back by money. What words would you use to describe the process of science as it occurred in this history of sequencing the human genome? Explain your choice(s). T/I C

8.6 Explore an Issue in DNA Forensics

Should DNA Samples Be Collected from Everyone?

The emergence of DNA evidence in the courtroom, several decades ago, has transformed the criminal justice system. DNA evidence collected at crime scenes and from possible suspects has proven to be a powerful tool for police. Investigators have used DNA evidence to solve decades-old cold cases and exonerate innocent people who had been convicted (**Figure 1**).

In June 2000, the National DNA Data Bank was founded in Canada. It is maintained by the Royal Canadian Mounted Police in Ottawa. It is used to preserve the DNA of all known convicted criminals (about 200 000 individuals) as well as 65 000 DNA evidence samples found at crime scenes. Investigators can compare DNA from a new crime scene with DNA from the data bank to see if they can find a match. As well, Canadian DNA data are shared with other police forces around the world. WEB LINK

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

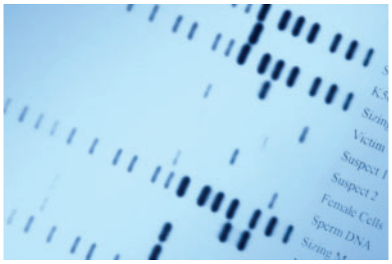


Figure 1 DNA analyses easily show crime investigators which suspect's DNA matches DNA found at a crime scene and which does not.

The Issue

Some people think that an individual's right to privacy may be infringed upon when a DNA sample is collected. People on one side of the issue suggest that once a crime has been committed, an individual forfeits this right to privacy. People on the other side believe that access to an individual's DNA is too intrusive, especially if the individual is only a suspect and has yet to be charged with a crime.

The federal and provincial governments have legislated parameters to determine whose DNA is eligible for inclusion in the data bank. The legislation needs to reflect the current sentiment with respect to DNA collection. For example, the legislation must consider who is required to submit DNA.

- Should shoplifters be required to submit DNA samples, or only murderers?
- Should all Canadians provide DNA samples at birth or upon immigration to our country?
- Should all visitors to Canada submit DNA samples?

This leads to another question: Who is a criminal? Is it fair to collect DNA from everyone involved in a crime, even innocent people? The British government decided that too many samples had been collected from innocent people and these samples should be discarded from their DNA database.

The Canadian government has been asked to review the current parameters that are used to determine whose DNA is stored in the data bank and for how long. You are one of several Members of Parliament who have volunteered to work on this issue and present your findings and viewpoint to the Parliament of Canada for consideration.

Goal

To conduct research and prepare recommendations to the Parliament of Canada regarding

- the right of Canadian law enforcement agencies to collect DNA samples
- the specific reasons that would allow law enforcement agencies to collect the samples
- the rights of the individuals from whom these samples are collected
- the length of time that the DNA samples should be stored

Research

SKILLS HANDBOOK A4

Find some of the annual reports of Canada's National DNA Data Bank. These reports contain real-life crime-solving stories. You might also want to research the following information, as well as other information that interests you: WEB LINK

- cases in which DNA evidence has been used to convict a criminal in court or to convince a criminal to confess to a crime
- cases in which people who were wrongfully convicted have been exonerated (**Figure 2**)
- other types of evidence, besides DNA evidence, that must be presented in court to support conviction or exoneration
- the cost of storing the data and maintaining privacy at the National DNA Data Bank
- the work of the federal Privacy Commissioner with respect to DNA sample collection and individual privacy

Figure 2 Kyle Unger speaks to reporters after being acquitted in 2009. His 1992 first-degree murder conviction was based on a hair found at the scene. The hair was retested with newer DNA technology and found not to be an incriminatory match.

Possible Solutions

Many different decisions can be reached on this issue. Below are six possible decisions, but you are encouraged to consider others.

- All Canadians, non-Canadian immigrants, and visitors to Canada should have a DNA sample stored in the data bank for their lifetime or a period of 100 years (to allow cold cases to be solved).
- If a person is convicted of a serious crime, his or her DNA should be stored in the data bank for one decade only.
- If a person is charged with any crime, his or her DNA should automatically go into the data bank.
- No citizen's DNA should be collected or stored.
- All citizens should be able to have their DNA record removed from the data bank.
- All citizens should be able to choose whether or not their DNA is stored in the data bank, regardless of their criminal record.

Decision

Decide under what circumstances DNA should be collected and stored by governments and law enforcement agencies. What rights do individuals have when being requested to provide a DNA sample? In addition, decide how long an individual's DNA should be stored in the Canadian DNA data bank. Should this depend on the criminal record of the individual?

Communicate

Hold a mock Parliamentary Committee meeting in your class. Each class member is a Member of Parliament and should provide his or her own arguments, research, and evidence.

Plan for **Action**

When your class has made its decisions in the Parliamentary Committee, prepare a pamphlet for the public that explains the rules and regulations regarding the collection and storage of DNA. Remember to consider your audience when you write the pamphlet.

WEB LINK

CHAPTER 8 Investigations

Investigation 8.1.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Transformation of Bacteria with the Gene for Green Fluorescent Protein

In this investigation, you will genetically modify an *E. coli* bacterium by inserting a plasmid. The plasmid contains a jellyfish gene that produces a green fluorescent protein (GFP), an ampicillin-resistant gene, and a special promoter sequence. If the transformation is successful, the bacteria will translate and transcribe the GFP gene, causing them to glow bright green under UV light.

Testable Question

How efficient is the transformation protocol in terms of the number of colonies of green fluorescent bacterial cells formed?

Prediction

After reading the experimental design and procedure, predict the growth of transformed pGLO bacteria on LB/amp and LB/amp/ara, and the growth of non-transformed pGLO bacteria on LB/amp and LB media.

Variables

What are the dependent and independent variables in this investigation?

Experimental Design

SKILLS HANDBOOK A2.2

In this investigation, you will compare bacteria (*E. coli* strain HB101) transformed with pGLO with bacteria non-transformed with pGLO. The pGLO plasmid contains the beta-lactamase gene, which codes for ampicillin resistance. Bacteria that have taken up the pGLO plasmid will grow on an agar plate that contains ampicillin.

Not every bacterium will receive a copy of the plasmid containing the pGLO plasmid. You should be able to distinguish between the two strains of bacteria by examining the traits they express when grown on LB agar plates with different additives. LB (Lysogeny Broth) is a rich agar medium that has been designed to support the growth of *E. coli* bacteria.

The pGLO gene is controlled by a promoter that is only active in the presence of the sugar arabinose. The AraC protein is coded by the *araC* gene on the plasmid and is a transcription factor. A transcription factor turns transcription "on" or "off," depending on environmental conditions. If arabinose is present in the growth medium, it binds to the AraC protein and changes its conformation. With this change in shape, RNA polymerase is able to bind and transcribe the GFP gene, producing the GFP protein.

In this investigation, you will plate and observe the growth of transformed and non-transformed bacteria on the following agar plates: +pGLO LB/amp, +pGLO LB/amp/ara, –pGLO LB/amp, and –pGLO LB. Bacteria that have been subjected to the transformation protocol are designated as +pGLO, while bacteria that have not are designated as –pGLO. Some colonies will fluoresce under UV light, and some will not. Once you have completed this investigation, you will be able to identify the independent and dependent variables. You will also be able to identify any controls used.

Equipment and Materials

SKILLS HANDBOOK A1

- safety goggles
- lab apron
- non-latex gloves
- 2 sterile 1.5 mL microfuge tubes
- permanent marker
- sterile transfer pipettes (10)
- sterile loops (8)
- LB agar plate (1)
- LB amp plate (2)
- LB amp/ara plate (1)
- micro-tube rack
- 37 °C incubator
- micropipette and tips (10 mL to 1000 mL)
- sterile LB broth (600 mL)
- ice-water bath
- masking tape
- 50 mM $CaCl_2$ transformation solution (600 mL)
- pGLO plasmid DNA
- bacterial strain HB101
- bleach (1:30 dilution)

Procedure

1. Put on your safety goggles and lab apron.
2. From your teacher, obtain the specific procedure that accompanies the experimental kit you will be using. The procedure is composed of the following sections:
   A. preparation of bacterial suspensions
   B. introduction of plasmids to cultures
   C. transformation of bacteria by heat shocking
   D. incubation
   E. culturing of bacteria on various media

Use disposable gloves to perform the experiment.

All the equipment you use, such as the loops and pipettes, must be sterilized.

Spin the loop gently between your index finger and thumb until the entire colony is dispersed in the transformation solution, with no floating chunks.

Tap the micro-tube containing the experimental material with a finger to ensure proper mixing.

If the pipettes are not the dropper type, use a pipette pump. Never pipette by mouth.

Do not breathe the bleach fumes.

When you are finished, place your equipment in an area designated by your teacher for proper disposal and sterilization.

Clean your lab space, and wash your hands thoroughly with soap when you are finished.

Observations

Draw a table like **Table 1** in your notebook to record your observations.

Table 1

Plate	Number of colonies and colour	General description of colonies	Description of colonies under UV light
+pGLO LB/amp			
+pGLO LB/amp/ara			
−pGLO LB/amp			
−pGLO LB			

Analyze and Evaluate

(a) What is the purpose of each plate and the medium it holds? T/I
  (i) +pGLO LB/amp
  (ii) +pGLO LB/amp/ara
  (iii) −pGLO LB/amp
  (iv) −pGLO LB

(b) On which plate did the most bacteria grow? Explain why. T/I

(c) On which plate did the least bacteria grow? Explain why. T/I

(d) What does the bacterial growth pattern in the two control plates indicate? T/I

(e) One of the plates contained bacteria with the pGLO plasmid, but did not fluoresce when examined with UV light. Which plate was this, and why did the colonies not glow? T/I

(f) In the −pGLO tube, there was no DNA present to transform into the cells. Why did this tube still need to go through the shock procedure? T/I

Apply and Extend

(g) Predict what would happen to the bacteria on the +pGLO LB/amp plate if you added arabinose sugar. T/I

(h) Distinguish between the genes and the proteins in this investigation. T/I

(i) How do your data compare with your prediction? T/I

(j) What are the two requisites that transform bacteria into colonies of green fluorescent bacterial cells? K/U

(k) What is the advantage, for an organism, of being able to turn a gene on or off depending on the environment? T/I

(l) The discovery of the GFP protein was recognized with a Nobel Prize. Using the Internet or other resources, research the following. T/I
  (i) Who discovered the GFP protein?
  (ii) What year and in which discipline was the Nobel Prize awarded for the GFP protein?
  (iii) Why did the discovery of the GFP protein merit a Nobel Prize?
  (iv) How can the GFP protein be used in medical research?

WEB LINK

Investigation 8.2.1 ACTIVITY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Looking for *Wolbachia*

Biologists have recently discovered that a surprising number of insect species are host to endosymbiotic bacteria. These bacteria, of the genus *Wolbachia*, not only live inside the cells of the host insect, but also have a dramatic influence on the reproductive success of the insect. For example, some female insects infected with the bacteria are able to reproduce parthenogenetically—without a male! Geneticists can identify insect species that harbour *Wolbachia* by extracting all the DNA contained within the insect cells and then using PCR followed by gel electrophoresis to test for the presence of *Wolbachia* DNA.

In this investigation, you will simulate the steps that are used to identify host species by looking for evidence of *Wolbachia* DNA.

Purpose

To simulate testing for the presence of endosymbiotic *Wolbachia* bacteria using forensic DNA technology

Equipment and Materials

- organism information card (for an insect or *Wolbachia*)
- scissors
- metre stick (or ruler)
- 3 m of string

Experimental Design

Geneticists use DNA fingerprinting techniques to determine which insects are host to endosymbiotic bacteria. In this investigation, you will simulate the following key steps:

1. DNA is extracted from pure *Wolbachia* cells and digested by a chosen restriction enzyme. This will produce several fragments that are characteristic of the bacteria's genome.
2. The same restriction enzyme is used to digest samples of DNA that are extracted from insect cells. This second digestion will produce many fragments of insect DNA. If *Wolbachia* bacteria are present in the insect cells, the digestion will also produce the characteristic *Wolbachia*-sized fragments.
3. Multiple copies of the DNA fragments are made using PCR.
4. The sizes of the fragments of the pure *Wolbachia* DNA and/or extracted insect DNA from each sample are compared using gel electrophoresis.

Procedure

1. Obtain an organism information card, as well as scissors, string, and a metre stick.

Part A: Simulating a Restriction Enzyme Digest

2. Using the restriction enzyme data on the information card, cut the string to the appropriate lengths. These pieces of string represent the DNA fragments that are produced when the DNA in your sample is digested by the restriction enzyme.

Part B: Simulating PCR

3. Model the effects of PCR by making one or more "copies" of your DNA fragment lengths.

Part C: Simulating Gel Electrophoresis

4. Go to the Gel Electrophoresis Station in the classroom. Stand at a location that represents a well at the negative end of the gel. If you have a *Wolbachia* information card, use an outer lane.
5. Model the migration of the DNA fragments by moving your fragments toward the positive end of the gel. Use the scale provided by your teacher to determine the precise locations where you should place your different-sized fragments. These locations represent the bands in a DNA fingerprint.

Analyze and Evaluate

(a) Compare the locations of the fragments for all the insect samples with those for the *Wolbachia* samples. Which insect samples had bands that matched those of *Wolbachia*? T/I

(b) What does a match tell you about the DNA fragments? T/I

(c) Which insects appear to contain the *Wolbachia* bacteria? T/I

(d) Why is a lack of matching bands considered very strong evidence that the insects do not have the endosymbiotic bacteria? T/I

(e) Suggest an explanation for why all the insect samples had more fragments than the *Wolbachia* samples. T/I

(f) What is the purpose of performing PCR on DNA samples? In an actual experiment, what problem would occur if this step were skipped? T/I

(g) Why did you first stand near the negative terminal of the gel? T/I

(h) Explain why the smallest fragments move a greater distance than the larger fragments in the same time. T/I

Apply and Extend

(i) Did any of the non-*Wolbachia* bands match? If so, what might this suggest about these particular insects? T/I

(j) Predict what the outcome would have been if you had used a different restriction enzyme. How might the fragment length data have been different? What differences would there have been in the locations and matches in the gel? T/I A

(k) Conduct online research to learn more about the endosymbiotic relationship between *Wolbachia* bacteria and their insect hosts. T/I

  (i) What kinds of insects are known to be hosts to *Wolbachia*?

  (ii) How does the presence or absence of *Wolbachia* influence sexual reproduction in these insects?

  (iii) Do you believe that this endosymbiotic relationship benefits or harms the insects or the bacteria? Explain your reasoning.

WEB LINK

CHAPTER 8 SUMMARY

Summary Questions

1. Review this chapter by looking at the Key Concepts in the margin on page 364. What did you learn that was new? Make a few point-form notes.
2. Many of the vocabulary words in the following list are related. Create at least three groupings of related words, and explain their relationships.

Vocabulary

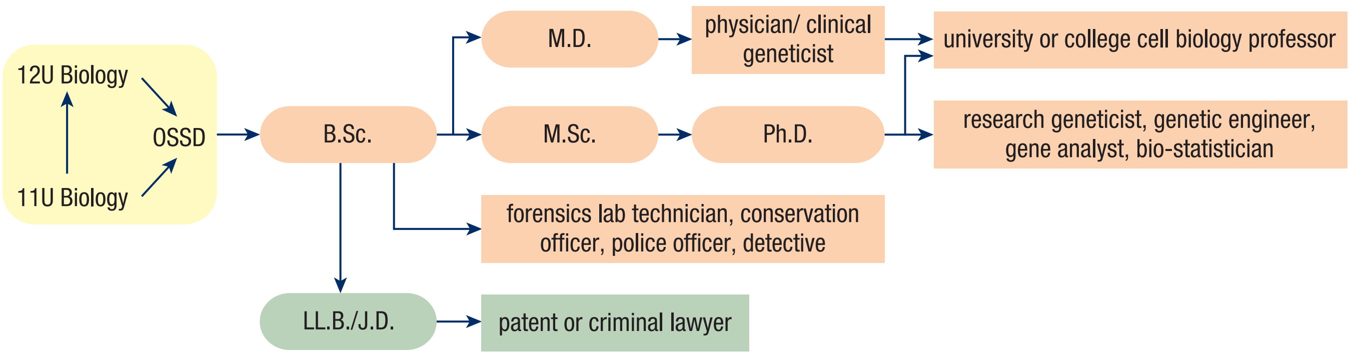
diabetes mellitus (p. 366)
type 1 diabetes (p. 366)
type 2 diabetes (p. 366)
genetic engineering (p. 366)
recombinant DNA (p. 366)
restriction enzyme (p. 366)
recognition site (p. 366)
restriction fragment (p. 366)
blunt end (p. 367)
sticky end (p. 367)
competent cell (p. 368)
vector (p. 368)
copy number (p. 368)
host cell (p. 368)
cloned gene (p. 368)
restriction map (p. 369)
hybridization probe (p. 374)
polymerase chain reaction (PCR) (p. 376)
DNA primer (p. 376)
gel electrophoresis (p. 378)
molecular marker (p. 379)
ethidium bromide (p. 379)
DNA sequencing (p. 379)
whole-genome shotgun method (p. 380)
structural genomics (p. 382)
functional genomics (p. 382)
bioinformatics (p. 382)
DNA microarray (p. 383)
biopharming (p. 386)
transgenic organism (genetically modified organism, GMO) (p. 386)
gene therapy (p. 391)
germ-line gene therapy (p. 391)
somatic gene therapy (p. 391)
genetic screening (p. 393)
amniocentesis (p. 393)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to genetic technologies that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.


12U Biology
11U Biology
OSSD
B.Sc.
M.D.
physician/ clinical geneticist
university or college cell biology professor
M.Sc.
Ph.D.
research geneticist, genetic engineer, gene analyst, bio-statistician
forensics lab technician, conservation officer, police officer, detective
LL.B./J.D.
patent or criminal lawyer

CAREER LINK

CHAPTER 8 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What is the molecular tool that scientists use to cut a DNA fragment from a larger piece of DNA? (8.1) K/U
   (a) DNA primase (c) methylase
   (b) restriction enzyme (d) DNA ligase
2. After excising a DNA fragment that contains a target gene, what should a molecular biologist do? (8.1) K/U
   (a) introduce the vector into a suitable organism
   (b) isolate the desired gene or DNA fragment
   (c) select the transformed cells
   (d) insert the gene into a vector
3. Which chemical compound can be used to stain a completed electrophoresis gel? (8.2) K/U
   (a) ethidium bromide (c) molecular marker
   (b) loading dye (d) DNA polymerase
4. During PCR, double-stranded DNA is separated into two single strands of DNA. What is this step called? (8.2) K/U
   (a) splicing (c) extension
   (b) denaturation (d) annealing
5. After 8 PCR cycles, how many target sequences have been synthesized? (8.2) K/U
   (a) 8 (c) 240
   (b) 16 (d) 256
6. What has prevented the introduction of genetically modified (GM) crops in Canada? (8.3) K/U
   (a) the risk that the GM crops may become invasive
   (b) the risk that genes may be transferred into the native population
   (c) the risk that they may continue to be resistant to herbicides and become a weed plant
   (d) all the above
7. What are knockout mice? (8.3) K/U
   (a) mice that have had one copy of a gene removed
   (b) mice that have had both copies of a gene removed
   (c) mice that have both copies of a gene turned on
   (d) mice that have both copies of a gene turned off
8. Why is somatic gene therapy used in humans rather than germ-line gene therapy? (8.4) K/U
   (a) Only somatic cells can take up the introduced genes.
   (b) Some patients have developed cancer from germ-line gene therapy.
   (c) The benefits of germ-line gene therapy are only temporary.
   (d) People have ethical objections to germ-line gene therapy.
9. How does genetic therapy differ from traditional methods of treating a disease? (8.4) K/U
   (a) It targets the effects of the disease.
   (b) In some cases, it fixes the genetic code itself.
   (c) It reverses the damage done to the body.
   (d) It replaces the need for organ transplant.
10. What did Palmiter and Brinster's experiments with mice show? (8.4) K/U
    (a) Transgenic genes can reduce but not eliminate a genetic defect.
    (b) Organisms can receive transgenic genes after being born.
    (c) Transgenic genes can correct a mutation in mammals.
    (d) The procedures that are used on mice cannot be used on humans.

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Increasing the copy number in a plasmid causes more protein to be transcribed. (8.1) K/U
12. Restriction enzymes recognize and bind to a specific sequence on a DNA strand. (8.1) K/U
13. Using a restriction enzyme that cuts a plasmid in two places will result in three fragments. (8.1) K/U
14. The polymerase chain reaction (PCR) enables scientists to produce millions of copies of a specific DNA sequence in approximately 2 h. (8.2) K/U
15. During PCR, only one DNA primer is needed, but it must be complementary to one end of the targeted area. (8.2) K/U
16. One of the main advantages of PCR is that only a small biological sample is needed. (8.2) K/U
17. Gel electrophoresis uses the principle that smaller fragments of DNA migrate faster through an agar gel than larger fragments. (8.2) K/U
18. Biopharming introduces new genes into a single animal, plant, or fungus to produce economically important proteins and enzymes. (8.3) K/U
19. Genetic screening can be used to determine whether a person has an inherited genetic disorder. (8.4) K/U
20. The effects of any modifications that are made by human somatic gene therapy are restricted to the individual and will not be inherited by any offspring. (8.4) K/U

Go to Nelson Science for an online self-quiz.
WEB LINK

CHAPTER 8 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Why are bacteria particularly useful for genetic engineering? (8.1) K/U
   (a) because of their plasmids
   (b) because of their recombinant DNA
   (c) because of their DNA strands
   (d) because of their RNA
2. Which substance can be used to increase the ability of a bacterial cell to incorporate plasmid DNA by stabilizing its cell membrane? (8.1) K/U
   (a) calcium chloride
   (b) chlorophyll
   (c) cellulose
   (d) ethyl alcohol
3. What is the first step in the polymerase chain reaction (PCR)? (8.2) K/U
   (a) annealing the DNA primers
   (b) building a complementary DNA strand between the primers
   (c) placing the solutions in an ice-water bath
   (d) separating the strands of DNA
4. Why can nucleic acids be investigated with gel electrophoresis analysis? (8.2) K/U
   (a) because of the charge-to-mass ratio of a nucleic acid molecule
   (b) because of the size of a nucleic acid molecule
   (c) because of the polarity of a nucleic acid molecule
   (d) because of the uniqueness of a nucleic acid molecule
5. DNA microarrays are an important tool in gene analysis. What do they allow scientists to do? (8.2) K/U
   (a) measure the expression levels of large numbers of genes simultaneously
   (b) determine the sequence of a DNA sample
   (c) measure the sizes of different genes
   (d) discover the locations of certain probe sequences
6. Higher vertebrates that are domesticated are used as models for genetic engineering. Why? (8.3) K/U
   (a) They are readily available.
   (b) They pose fewer environmental risks to ecosystems.
   (c) They are easier to work with than bacteria.
   (d) They can produce larger, more complex molecules and protein products that can easily be harvested.
7. What is the goal of the movement to raise heirloom varieties? (8.3) K/U
   (a) maintain genetic diversity in agriculturally significant species
   (b) protect a species from population crashes
   (c) maintain a reserve of genes that can be bred into other strains
   (d) all of the above
8. Which type of information can an amniocentesis test determine? (8.4) K/U
   (a) if either of the parents of a child have chromosomal abnormalities
   (b) if germ-line gene therapy should be performed before conception
   (c) if a man and a woman have chromosomal abnormalities that would prevent conception
   (d) if a fetus has chromosomal abnormalities
9. Which treatment for potential hereditary diseases is the least invasive? (8.4) K/U
   (a) laser surgery
   (b) germ-line gene therapy
   (c) repeated enzyme injections
   (d) regulation of diet

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Replacement insulin for diabetics was first collected from the bacteria *E. coli*. (8.1) K/U
11. If a restriction enzyme cuts straight across the strand, a sticky end results. (8.1) K/U
12. A plasmid is a DNA molecule that is separate from, and can replicate independently of, the chromosomal DNA. (8.1) K/U
13. During the annealing step in PCR, the DNA primers bind to the DNA at a lowered temperature. (8.2) K/U
14. During gel electrophoresis, negatively charged DNA fragments travel through a gel, away from a positive electrode at the starting end and toward a negative electrode at the destination end. (8.2) K/U
15. Transgenic animals or plants are more commercially viable than bacteria due to their ability to produce larger, more complex proteins. (8.3) K/U
16. Seed banks collect and store heirloom varieties of food plants to protect natural levels of genetic diversity. (8.3) K/U
17. The expression of a disease in a person's phenotype may be controlled through various strategies, including non-invasive strategies. (8.4) K/U

18. The National DNA Data Bank in Ottawa was established to store the genetic identities of all Canadians born after 2000. (8.6) K/U

Match each term on the left with the most appropriate description on the right.

19. (a) knockout mice
    (b) biopharming
    (c) competent cell
    (d) transgenic plants
    (e) GMO

    (i) able to resist herbicides
    (ii) able to take up foreign DNA
    (iii) homozygous for one inactive gene
    (iv) containing genes from another species
    (v) using agriculture to harvest large-scale engineered proteins (8.3) T/I

Write a short answer to each question.

20. What is the function of DNA ligase? (8.1) K/U
21. When using restriction enzymes, biologists prefer to work with restriction enzymes that produce sticky ends in DNA fragments. Explain why. (8.1) K/U
22. When using calcium chloride to promote transformation, why must the solution be heated and then quickly re-cooled? (8.1) K/U
23. (a) How does DNA ligase anneal two DNA strands?
    (b) Why is this bond more permanent than the initial formation? (8.1) K/U
24. Using an example, explain the term *palindromic* in terms of restriction enzymes. (8.1) K/U
25. What molecular biology technologies can be used to help protect wildlife? How is this done? (8.2) K/U
26. List and briefly describe the three steps of the polymerase chain reaction (PCR). (8.2) K/U
27. Compare and contrast the chain termination, whole-genome shotgun, and nanopore methods of DNA sequencing. (8.2) K/U
28. What are researchers looking for when they perform sequence similarity searches? (8.2) K/U
29. Why do researchers use DNA microarrays? (8.2) K/U
30. Define and briefly describe biopharming. (8.3) K/U
31. Define a transgenic organism and give three examples: one animal, one plant, and one bacterium. (8.3) K/U
32. What causes PKU and how is it treated? (8.4) K/U
33. Why are researchers not giving germ-line gene therapy to humans? (8.4) K/U
34. Briefly describe the Human Genome Project. What was its purpose? (8.5) K/U

Understanding

35. Explain why the formula $\frac{1}{4^n}$ is used to represent the probability of finding a recognition site. (8.1) K/U
36. Draw the formation of a phosphodiester bond that results from DNA ligase. (8.1) K/U C
37. Explain the steps in the laboratory technique used to increase the likelihood that a bacterial cell will undergo a genetic transformation. (8.1) T/I
38. (a) What is the function of restriction enzymes in nature?
    (b) Explain how the discovery of restriction enzymes helped scientists advance DNA technology. (8.1) T/I
39. Describe two ways that plasmids are beneficial to prokaryotic cells. (8.1) T/I
40. (a) What is a hybridization probe, and how is it used?
    (b) Why does a hybridization probe have to be highly specific?
    (c) How can hybridization be used in insulin production? (8.1) K/U T/I
41. Explain how *E. coli* is used as a vector to produce synthetic insulin. (8.1) K/U T/I
42. Why might a restriction enzyme that recognizes a short sequence pose a problem for scientists who are trying to excise a single gene? (8.1) T/I
43. Use a flow chart to summarize the overall steps that scientists use to engineer a plasmid. (8.2) K/U C
44. In nanopore sequencing, holes that are only 2.5 nm in diameter are used to sort nucleotides. How big is 2.5 nm in centimetres? (8.2) T/I
45. Imagine that you work for a medical research facility. You have been asked to create an informative pamphlet for students to explain why molecular biologists are creating transgenic plants and animals for the agricultural industry. What information will you put in the pamphlet? (8.3) K/U T/I C
46. Use a Venn diagram to compare and contrast germ-line gene therapy and somatic gene therapy. (8.4) K/U C

Analysis and Application

47. Identify and complete the complement of the palindromic sequence in this single strand of DNA: 5′-TACCTACGAAGCTTATCGCCCGC-3′. (8.1) T/I
48. Use mathematics to explain why a four-base-pair recognition site for a restriction enzyme is more likely to lead to more cuts in a DNA sequence than a six-base-pair recognition site. (8.1) T/I

49. Use **Table 1** to lyse the following sequence of DNA twice:

5′-TTATTATTAAAGCTTCTCGAATTCGAGAAG
CTTGGTCCCC-3′

3′-AATAATAATTTCGAAGAGCTTAAGCTCTTC
GAACCAGGGG-5′ (8.1) T/I

Table 1 Restriction Enzyme Recognition Sites

Name of enzyme	Recognition site
EcoRI	5′-GAATTC-3′ 3′-CTTAAG-5′
XhoI	5′-CTCGAG-3′ 3′-GAGCTC-5′
HindIII	5′-AAGCTT-3′ 3′-TTCGAA-5′
SmaI	5′-ACCCGGGT-3′ 3′-TGGGCCCA-5′

50. **Figure 1** shows a sketch of a gel that was produced when bacteriophage DNA was digested with HindIII. The fragments of HindIII were 25 000 bp, 9416 bp, 6557 bp, 4361 bp, 2322 bp, and 2027 bp, and they were run in lane A. Using these fragment lengths as size standards, determine the fragment lengths of the bands that appear in lanes B and C. You will have to measure the distances that the HindIII bands have travelled and plot a semilogarithmic graph (distance travelled versus base-pair size). (8.1) T/I

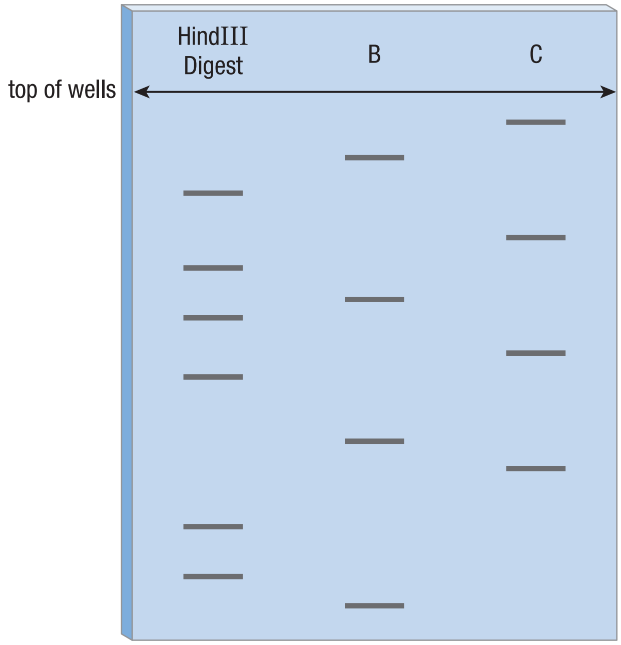


Figure 1

51. Develop a mathematical formula to relate the number of fragments that result from cutting a plasmid and a eukaryotic chromosome using a restriction enzyme. (8.1) T/I

52. **Figure 2** shows a plasmid that was digested with several restriction enzymes. The area that is identified as tet^r contains a gene for tetracycline resistance. (8.1) K/U T/I C

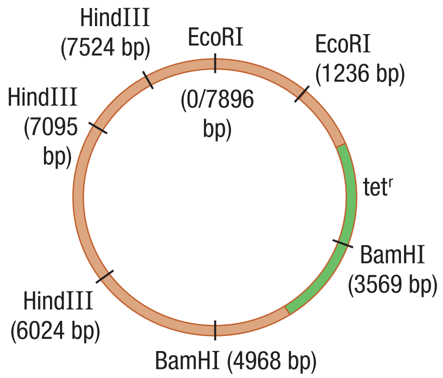


Figure 2

(a) Determine the length of the plasmid.

(b) Use a table to identify the fragments that resulted from digestion with each of the following restriction enzymes: EcoRI, BamHI, and HindIII.

(c) In the same table, identify the fragment that resulted from digestion with EcoRI and HindIII together.

(d) In the same table, identify the restriction fragments that resulted from digestion with EcoRI, BamHI, and HindIII together.

(e) Which enzyme should not be used on this plasmid? Why?

(f) Sketch the resulting gel.

53. Following digestion of a plasmid with a sequence of restriction enzymes, the following fragments were found: 2.6 kbp, 1.6 kbp, 3.4 kbp, 1.3 kbp, 0.5 kbp, and 1.1 kbp. (8.1) T/I C

(a) Sketch the resulting electrophoresis gel after running the fragments in it. Assume that the fragments were all run in one lane. Label the positions of the positive and negative electrodes.

(b) Which two fragments may be difficult to isolate in a gel? Why?

(c) What could you do to improve the resolution of the gel?

54. Predict the number of cuts that would result from cutting a fragment of DNA that has 200 000 bp with a restriction enzyme that has a 5 bp recognition sequence. What is the average frequency of the cuts? (8.2) K/U T/I

55. (a) Use a flow chart to show the process of PCR through the first two replications, using the DNA fragment in **Figure 3**.
    (b) Explain why no target sequences are created through the first two replications.
    (c) What will happen in the third replication?
    (d) What would be the sequences of the forward and reverse primers? (8.2) K/U T/I C

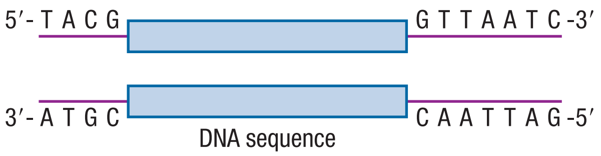


Figure 3

56. A geneticist wants to insert the gene that expresses the glowing protein in jellyfish into *E. coli*. To ensure success, gene transfer and uptake need to be done on plates that contain arabinose and ampicillin. Create a flow chart to describe, in detail, the steps that are required to insert the jellyfish gene into *E. coli*. Use **Figure 4** for reference, as well as your knowledge of restriction enzymes, DNA ligases, methylases, plasmids, and selective plating. (8.2) T/I C

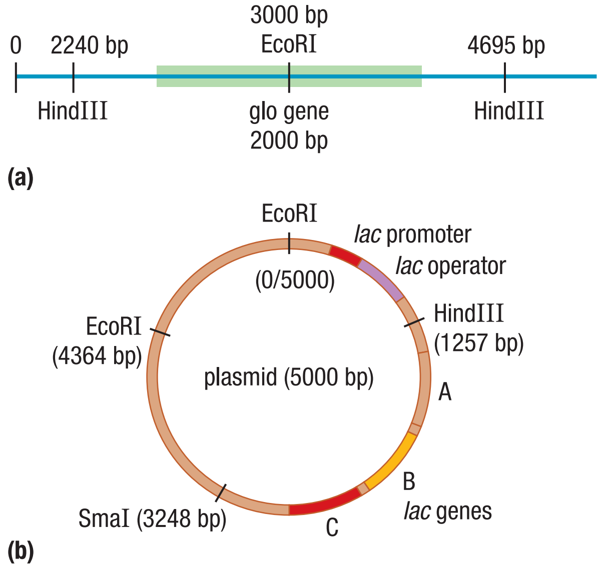


Figure 4 (a) Source fragment and (b) plasmid

57. (a) Use a graphic organizer to compare the two types of genome analysis: structural genomics and functional genomics.
    (b) Which type of genome analysis could make use of microarray technology? Explain why. (8.2) K/U T/I

58. “Genome sequencing has revealed many significant features of genetic organization.” Evaluate the accuracy of this statement, using examples to support your opinion. (8.2) T/I

59. Plasmid pBR322 includes two genes that confer antibiotic resistance: a gene for ampicillin and a gene for tetracycline. The cutting site for the restriction enzyme BamHI is in the middle of the tetracycline resistance gene. The cutting site for the restriction enzyme PvuI is in the middle of the ampicillin resistance gene. If you were using a cell culture plate that contained ampicillin, which restriction enzyme (BamHI or PvuI) would you use to cut the plasmid and excise the gene you wanted to insert into the plasmid? Explain. (8.2) T/I

60. Two restriction enzymes are used to lyse a plasmid. Subsequent electrophoresis revealed the data in **Table 2**. Construct a restriction map for this plasmid. (8.2) T/I C

Table 2

EcoRI	HindIII	EcoRI and HindIII
1000 bp	850 bp	300 bp
750 bp	900 bp	400 bp
		600 bp
		450 bp

61. Summarize the methods that scientists use to control genetic diseases. Identify the method that is the most invasive. (8.3) T/I

62. Suppose that you work for the Ontario Ministry of Natural Resources, in a genetics lab. You have been asked to identify a fish that was confiscated during a recent weekend enforcement blitz. The enforcement officers suspect that the fish was caught out of season, but they cannot determine its identity so they have asked you to run a DNA analysis. Does the evidence shown in **Figure 5** support the officers’ suspicion? Explain your reasoning. (8.6) T/I

Evaluation

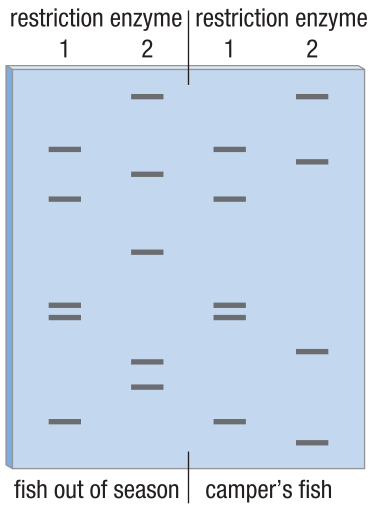


Figure 5

63. Create an informative poster with a flow chart that identifies and describes the six main steps in genetic engineering. (8.1) K/U C

64. "Experimental biology has been changed by the development of DNA technologies that can analyze genes and gene expression." Write a brief report to support this statement, using examples from the textbook. (8.1) T/I C

65. The creation of giant mice by Richard Palmiter at the University of Washington in 1983 was highly publicized by the media (**Figure 6**). Discuss the implications of Palmiter's work. (8.4) A

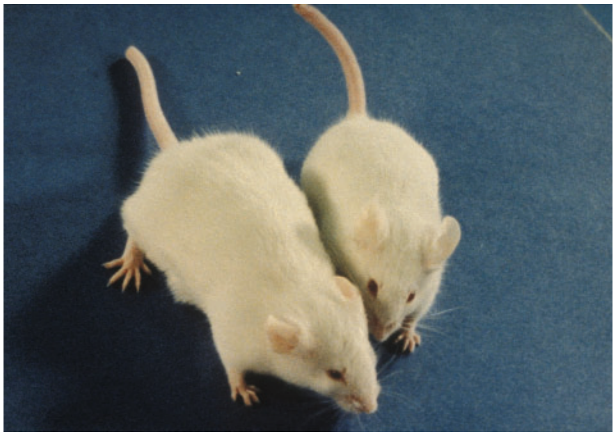


Figure 6

66. The following two analogies have been used to describe the whole-genome shotgun method: a shotgun blast, and several identical books separated into groups of pages and reassembled. (8.2) K/U T/I C
    (a) Describe the shotgun method.
    (b) Use a diagram and a paragraph to explain whether the analogies are appropriate.

67. If a host bacterium undergoing genetic engineering becomes resistant to antibiotics, what does this indicate? (8.1) K/U

68. (a) What is required for DNA ligase to rejoin DNA fragments?
    (b) How is this reaction catalyzed by DNA ligase like many other organic and body reactions? (8.1) K/U T/I A

69. One of the greatest feats of modern science has been deciphering the human genetic code. However, Dr. Craig Venter has suggested that the real feat will be to decipher the proteome. With the help of an analogy, develop an argument to support or refute his suggestion. (8.2) T/I A

70. The Human Genome Project selected *E. coli*, a yeast, fruit flies, *Caenorhabditis* (a nematode), and laboratory mice for genome sequencing. Defend their selection of these organisms to investigate initially. (8.2) T/I

71. Discuss some of the concerns associated with genetically modified organisms. Do you think that the benefits of GMOs outweigh these concerns? Explain your reasoning. (8.3) K/U T/I

72. Our society depends heavily on petroleum-based plastics. Are biodegradable plastics much better? Develop a position on the use of transgenic plants and prime farmland to produce biodegradable plastics as a replacement for petroleum-based plastics. (8.3) K/U T/I

73. (a) Describe how knockout mice are produced.
    (b) Explain why knockout mice are important to genetics research.
    (c) In the role of a lawmaker, prepare a series of guidelines for the use of knockout mice in scientific research. Should knockout mice be covered by animal cruelty laws to regulate how transgenic materials are inserted into their DNA? (8.3) K/U T/I A

74. Genetic privacy is an important issue that many countries have not dealt with. If you worked for the United Nations and were asked to develop a universal set of genetic rights, what would you include? Why? (8.3) T/I

75. Describe how somatic gene therapy has been successful in combating sickle-cell disease, but has failed in other applications. (8.4) K/U T/I

76. Evaluate the achievements in human somatic gene therapy since the 1990s. Decide whether you think the pros of human somatic gene therapy outweigh the cons. Justify your decision. (8.4) T/I C A

Reflect on Your Learning

77. In this chapter, you have learned about a variety of genetic technologies and issues. Which technology or issue did you find most interesting? Why? T/I

78. Suppose you have just discovered that you have a mutation in your DNA. What are some actions that you might want to pursue? T/I A

79. If you were given the opportunity to know your genetic profile, would you take this opportunity? What are the potential implications of knowing your genetic identity? T/I C A

80. Do you think Canadian citizens should have a Genetic Charter of Rights? Explain your thinking. T/I

Research

WEB LINK

81. Producers of transgenic plants often claim that these plants can feed millions of starving people. If this is possible, why is it not happening? Conduct research to support your answer. T/I

82. Using molecular genetics, Dr. Hendrik Poinar and others at the Ancient DNA Centre at McMaster University are providing valuable data to show how humans and our diseases have evolved. Prepare a brief portfolio about molecular anthropology and evolutionary genetics. Include answers to the following questions in your portfolio:
    - What are the goals of molecular anthropology and evolutionary genetics?
    - How do scientists recover old DNA and make it available for research? T/I C

83. Scientists have isolated and used a gene for green fluorescent protein (GFP) in many experiments. Use the Internet to research answers to the following questions. Prepare a short multimedia or graphical presentation to share your answers.
    - How has this gene been useful in research?
    - How could it help to reduce the use of medications in agriculture?
    - How might it prevent large-scale agricultural disease?
    - Why do you think the discovery of the GFP gene has gone unnoticed, even though the scientists who discovered its unique features have recently won a Nobel Prize? T/I C A

84. Research transformation techniques that have been developed to increase the rate of gene transfer. Prepare a brief report to share your findings. T/I

85. Molecular geneticists have developed a wide range of tools to investigate the functions and locations of genes. Prepare a short report to summarize how geneticists find and identify individual genes using fluorescent proteins with hybridization techniques. Why would fluorescence be preferred over the use of radionucleotides? T/I A

86. Conduct online research to learn about different types of gel electrophoresis. What is two-dimensional gel electrophoresis, and when is it used? T/I

87. Many agribusiness companies are criticized for designing crops with “kill genes.” Taking the role of a farmer or an agribusiness spokesperson, develop an argument for or against this type of genetic engineering and the use of “kill genes” in food crops. Consider the following questions as you develop your argument:
    - Why would these genes be used in food crops?
    - What are the social and environmental implications of these genes? T/I C A

88. Few scientists have won one Nobel Prize, yet Fredrick Sanger won two. Prepare a biography of Dr. Sanger. Identify his two contributions that were awarded Nobel Prizes. Explain how his research has changed our understanding of DNA and genetics, and how it has changed our lives. T/I

89. Use the Internet to research some of the concerns about biopharming. Which of these concerns do you find most significant, and why? T/I C A

90. Bioplastics might be a solution to the use of petroleum-based plastics. One chemical, PHB, could be a solution to plastic waste, since it is a biodegradable form of plastic. However, the high cost of its production has slowed progress. Research how scientists are trying to use transgenic organisms to produce PHB more affordably. T/I C A

91. The global seed bank in Svalbard, Norway, was designed to ensure the protection of many species of plants. How has the heirloom vegetable market revived interest in agriculture while ensuring genetic diversity? T/I C A

92. Current DNA fingerprint analysis uses PCR on short tandem repeats (STR), replacing variable number tandem repeats (VNTRs) analysis. PCR/STR analysis has been shown to be more reliable and more consistent for determining relatedness. T/I C
    (a) Investigate the benefits of STRs for the polymerase chain reaction.
    (b) Mathematically, why does the RCMP use 13 STR markers instead of 5 VNTRs, which can predict to a certainty of one in a billion?
    (c) How has DNA changed the shape of law enforcement both positively and negatively?

93. Jesse Gelsinger died from a severe immune response to gene therapy treatments. Conduct online research to learn what happened. Explain how Jesse’s situation illustrates the risks and unresolved issues associated with somatic gene therapy. T/I C

Biotechnology: Present and Future

The applications of biotechnology are becoming increasingly prevalent in our society. Biotechnology is a multidisciplinary pursuit that involves not only biology, but also chemistry, engineering, physics, and computing, to create innovative products and techniques. Health biotechnology, currently the largest sector in the Canadian biotechnology industry, involves the development of new therapies and drugs, vaccines, diagnostic procedures, and testing equipment. Agricultural biotechnology is increasingly used to mitigate the growing challenges of a changing climate (such as drought in many areas), malnutrition, and the environmental degradation caused by traditional industrial agriculture (**Figure 1**). Industrial biotechnology is creating new household and industrial products and processes that can provide innovative solutions for cleaning up environmental contamination, purifying water, and producing biodegradable detergents and solvents. These benefits, of course, come with risks. Some applications, such as forensic investigation and pharmaceutical production, are accepted without much notice or societal concern. Others, such as genetically modified and transgenic organisms, are the subject of considerable attention and ongoing debate.

Figure 1 A field of genetically modified canola

In this Unit Task, you will explore one application of biotechnology. You will research its history, its current and possible future applications, and any associated ethical or societal considerations. Based on your research, you will decide which direction (if any) future research should take.

The Issue

Should new research be conducted to further the development of this application of biotechnology in society? If so, where should the new research be focused?

Goal

Research one application of biotechnology. Your research should explore its development in terms of molecular and cellular processes; its past, present, and possible future uses; and any ethical and societal considerations attached to its development and uses.

Procedure

1. Choose an application of biotechnology from the list below, or have your teacher approve another application that interests you.
    - DNA fingerprinting for paternity testing
    - forensics and DNA fingerprinting
    - athletes and gene doping
    - genetically modified organisms, such as transgenic crops
    - DNA microarrays and cancer
    - gene-based therapeutic approaches
    - genetic testing and life insurance
    - pharmacogenetics
    - bioremediation, such as the use of biological organisms to clean up environmental damage
2. Investigate the science behind the biotechnological application you have chosen. Research how the application works. Include a flow chart that outlines the steps in the process.
3. Using your knowledge of some of the cellular processes discussed in this unit, draw parallels between your chosen application and any process that may occur naturally in a cell. For example, the development of the polymerase chain reaction (PCR) is based on the process of DNA replication (Section 8.2).
4. Draw a three-column table to help you take notes related to the past, present, and possible future uses of the biotechnological application.
5. Make a list of the ethical and societal considerations associated with the application. Subdivide the ethical and societal implications into subcategories. For example, societal implications can be divided into categories such as the beneficial uses and harmful effects of the application for society or specific members of society.

6. Decide whether future research should be conducted. Make a list of areas in which you feel that the biotechnological application should be further developed and areas in which you feel that research should stop.
7. Present your findings in the form of a poster, a 5-min presentation, or any other visual format approved by your teacher. Use charts and graphs, as needed, to illustrate your findings.

   Support your findings with reputable and published scientific sources, cited in the format provided by your teacher. Ask your teacher if you are not sure about the reliability of any of your sources. Keep in mind that the purpose of company websites is to promote their products. Therefore, such sites are not the best places to discover potential negative impacts of technologies that they are developing and/or selling. You will need to do some detective work by digging deeper and exploring a wider range of materials to find both the pros and cons of your chosen application.

Analyze and Evaluate

(a) Present the purpose of the biotechnological application you chose. Outline how it works using a flow chart or a diagram. T/I C

(b) Provide a historical summary of the development of the application. T/I

(c) Make any relevant connections between the application and DNA, protein synthesis, DNA replication, or any other cellular process. T/I A

(d) Summarize the past, present, and possible future uses of the application in table format. T/I C

(e) Create a summary table with pros on one side and cons on the other. List each societal concern related to the application in the appropriate column. T/I C

(f) Repeat Step (e) for ethical concerns. T/I C

Apply and Extend

(g) Propose other possible uses of the biotechnological application in the future. A

(h) How will prevalent use of the application affect society and our human genomes (if relevant)? A

(i) What is your personal stance on the use of the application? Do you agree or disagree with its use? A

(j) What knowledge gaps exist for the application? If you were in charge of allocating research funding to scientists working to improve the application, what specific research questions or areas would you fund first? Are there any areas in which further research should not continue? Why or why not? T/I A

(k) Prepare a presentation and share it with your class. T/I C

ASSESSMENT CHECKLIST

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

- ✓ Demonstrate your understanding of the purpose of your chosen biotechnological application and its process.
- ✓ Demonstrate your knowledge of the history of its development.
- ✓ Demonstrate your knowledge of its past, current, and possible future uses.
- ✓ Demonstrate your understanding of the parallels between the application and cellular processes.

Thinking/Investigation

- ✓ Propose, based on your background understanding, some possible future uses of the application.
- ✓ Demonstrate your understanding of the societal and ethical implications of using the application.

Communication

- ✓ Explain to the class the biotechnological application you researched, using an appropriate visual format.
- ✓ Present your research in flow charts and tables.
- ✓ Answer questions raised by your peers about your chosen application, using information from your research.

Application

- ✓ Propose some possible future uses for the biotechnology, perhaps extending those proposed in the sources you explored with some original ideas.
- ✓ Demonstrate your understanding of potential future ethical and societal considerations based on possible future uses of the application.
- ✓ Articulate your stance on whether the application is beneficial or harmful, and whether you agree with its use now or in the future.
- ✓ Explain the knowledge gaps with respect to the application: what is not known and what areas of research are most important for filling in the knowledge gaps.
- ✓ Decide whether the application should be further developed or whether research should stop.

UNIT 3 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which statement about haplodiploidy in bees is correct? (6.1) K/U
   (a) All males are haploid, and all females are diploid.
   (b) All males are diploid, and all females are haploid.
   (c) The queen is diploid; all the other females and all the males are haploid.
   (d) The queen, all the females, and a few mating males are diploid; all the other males are haploid.
2. What did Griffith's experiment show? (6.2) K/U
   (a) Bacteria cannot change their genetic material.
   (b) Bacteria can pass on their genetic material when they are dead.
   (c) Bacteria can take up genetic material from nearby bacteria and use it as their own.
   (d) Bacteria can take up genetic material from nearby organisms and use it as their own.
3. The nucleotides from a bacterial cell were found in the following abundances: adenine: 39.2 %; uracil: 40.7 %; cytosine: 9.1 %; guanine: 7.9 %. What type of molecule is it most likely to be? (6.2) K/U
   (a) double-stranded DNA
   (b) double-stranded RNA
   (c) messenger RNA
   (d) single-stranded DNA
4. Which problem in molecular genetics did Watson and Crick's model of DNA suggest a solution to? (6.3) K/U
   (a) DNA methylation
   (b) DNA replication
   (c) protein transcription
   (d) protein translation
5. Which of the following best describes DNA replication? (6.4) K/U
   (a) conservative
   (b) discontinuous
   (c) semiconservative
   (d) destructive
6. What feature allows histones to associate with DNA? (6.5) K/U
   (a) Histones are neutral and associate with deoxyribose.
   (b) Histones are negative and associate with positively charged DNA.
   (c) Histones are positive and associate with negatively charged DNA.
   (d) Histones are negatively charged and form dipole bonds with the hydroxyl groups on deoxyribose.
7. What does the Hayflick limit define? (6.6) K/U
   (a) how many times a cell can divide
   (b) how many proteins a cell can make
   (c) how much DNA can be removed from a dividing cell before it can no longer replicate
   (d) how telomerase can limit the repair of DNA
8. The human body contains more than 100 000 types of proteins. Approximately how many genes are thought to be needed to construct these proteins? (7.1) K/U
   (a) 10 000
   (b) 20 000
   (c) 100 000
   (d) 3 000 000 000
9. In eukaryotes, which RNA polymerase is used to transcribe protein-coding genes? (7.1) K/U
   (a) RNA polymerase III
   (b) RNA polymerase I
   (c) RNA polymerase II
   (d) all of the above
10. What provides the energy to bind polypeptides as the polypeptide chain elongates during translation? (7.2) K/U
    (a) ATP
    (b) GTP
    (c) $FADH_2$
    (d) NADH
11. What regulates repressor proteins? (7.4) K/U
    (a) environment
    (b) operator
    (c) promoter
    (d) all of the above
12. Which of the following could describe a genetic mutation? (7.5) K/U
    (a) positive
    (b) negative
    (c) silent
    (d) all of the above
13. What does comparative genomics seek to understand? (7.6) K/U
    (a) individual genetic sequences
    (b) how individuals in a family group vary in their genomes
    (c) how individuals in a species vary in their genomes
    (d) how species vary in their genomes

14. Why are viruses classified like living things? (7.7) K/U
    (a) They have DNA.
    (b) They have RNA.
    (c) They can replicate themselves.
    (d) They can replicate on their own.
15. How do scientists verify the successful uptake of a gene by a transformed cell? (8.1) K/U
    (a) by including antibiotic-resistance genes
    (b) by including heat-shock-resistance genes
    (c) by including fluorescence genes
    (d) all of the above
16. What is the chance of finding an eight-base-pair recognition site for a restriction enzyme? (8.2) K/U
    (a) 15.25 %
    (b) 1.525 %
    (c) 0.015 25 %
    (d) 0.001 525 %
17. Why are non-food plants good candidates for being genetically modified and being used to produce pharmaceuticals? (8.3) K/U
    (a) They can be grown close to human populations all over the world.
    (b) People do not eat them.
    (c) The agricultural infrastructure that is needed to grow them already exists.
    (d) all of the above
18. Which hereditary disorder is the best candidate for gene therapy? (8.4) K/U
    (a) adenosine deaminase deficiency
    (b) alpha-1 antitrypsin deficiency
    (c) cystic fibrosis
    (d) hemophilia

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

19. Prokaryotes and archaea can be distinguished from eukaryotes because they lack a membrane-bound nucleus surrounding their DNA. (6.1) K/U
20. Griffith showed that DNA was responsible for the transformation he saw in his experiments. (6.2) K/U
21. Franklin, Wilkins, Watson, and Crick shared the 1962 Nobel Prize as a result of their collaboration. (6.3) K/U
22. DNA replication is continuous on the lagging strand because DNA polymerase III only reads in the 5′ to 3′ direction. (6.4) K/U
23. Prokaryotes and archaea use linkers to join nucleosomes when forming chromatin. (6.5) K/U
24. Telomere length can be used to help determine the age of a cell. (6.6) K/U
25. The central dogma in genetics describes the flow of information from a protein to DNA. (7.1) K/U
26. Termination of transcription in eukaryotes can be the result of mRNA binding with itself or the cleaving of mRNA. (7.2) K/U
27. Amino acids are cleaved at the P site during polypeptide elongation. (7.3) K/U
28. Transcriptional regulation of proteins controls the availability of mRNA to ribosomes. (7.4) K/U
29. Gene amplification results when a gene sequence is read multiple times in the same locus. (7.5) K/U
30. Approximately 75 % of the human genome is considered intergenic. (7.6) K/U
31. The influenza A virus has a high rate of mutation because of its high rate of replication error. (7.7) K/U
32. DNA ligase is responsible for forming phosphodiester bonds in a hydration reaction that requires one water. (8.1) K/U
33. A cell that is used to transfer a genetic material into a new cell is known as a competent cell. (8.1) K/U
34. Hybridization probes are single-stranded complementary strands of DNA used to identify specific sequences on target DNA molecules. (8.1) K/U
35. Structural genetics is the science that looks at the locations and genetic sequences of a genome. (8.2) K/U
36. Electrophoresis relies on the charge of a DNA fragment to determine fragment size. (8.2) K/U
37. Because of its charge, DNA is attracted to the negative electrode during gel electrophoresis. (8.2) K/U
38. The polymerase chain reaction (PCR) uses both forward and reverse primers to replicate DNA. (8.2) K/U
39. Heirloom varieties are important to help maintain the genetic diversity of a species. (8.3) K/U
40. The use of plants could significantly reduce the cost of bioplastics, such as polyhydroxybutyrate (PHB), currently produced in micro-organisms. (8.3) K/U
41. PKU, hypercholesteremia, ADA, and cystic fibrosis are all genetic diseases that currently have working genetic therapies. (8.4) K/U
42. The Human Genome Project was a privately funded experiment to decode the human genome. (8.5) K/U

Knowledge

For each question, select the best answer from the four alternatives.

1. Why are archaea more like eukaryotes than prokaryotes? (6.1) K/U
   (a) because plasmids are associated with their DNA
   (b) because chromosomes are associated with their DNA
   (c) because nucleoids are associated with their DNA
   (d) because histones are associated with their DNA
2. Which radioisotopes did Hershey and Chase use in their experiments? (6.2) K/U
   (a) ^{15}N and ^{35}S
   (b) ^{32}P and ^{35}S
   (c) ^{32}P and ^{15}N
   (d) ^{32}P, ^{35}S, and ^{15}N
3. Why was Pauling and Corey's original model of DNA discredited? (6.3) K/U
   (a) because it was a two-stranded structure with the backbone on the outside
   (b) because it was a two-stranded structure with the backbone on the inside
   (c) because it was a three-stranded structure with the backbone on the outside
   (d) because it was a three-stranded structure with the backbone on the inside
4. Which enzymes are responsible for most DNA repair? (6.4) K/U
   (a) DNA polymerase I and II
   (b) DNA polymerase II and III
   (c) DNA polymerase I and III
   (d) DNA ligase
5. Which structures can aid in gene regulation? (6.5) K/U
   (a) histones
   (b) nucleosomes
   (c) solenoids
   (d) all of the above
6. When may some cells become cancerous? (6.6) K/U
   (a) when they use up their supply of telomerase
   (b) when they stop being able to respond to telomerase
   (c) when they start generating high amounts of telomerase
   (d) when they start interfering with the telomerase that is produced by their nearest neighbour
7. Why is RNA structurally different from DNA? (7.1) K/U
   (a) RNA is generally single stranded.
   (b) RNA is generally double stranded.
   (c) RNA is always read in the 5′ to 3′ direction.
   (d) RNA is always read in the 3′ to 5′ direction.
8. What is an example of post-transcriptional modification? (7.2) K/U
   (a) addition of a poly(A) tail
   (b) 5′ capping
   (c) removal of introns by spliceosomes
   (d) all of the above
9. What is the correct tRNA anticodon sequence for the 5′-ACT-3′ DNA sequence? (7.3) K/U
   (a) 5′-UGA-3′
   (b) 3′-UGA-5′
   (c) 5′-ACU-3′
   (d) 3′-ACU-5′
10. Why are masking proteins used by organisms? (7.4) K/U
    (a) They hide introns.
    (b) They hide exons.
    (c) They hide mRNA.
    (d) They hide ribosome-binding sites.
11. Which term refers to sequences of genes that can move freely through the genome? (7.5) K/U
    (a) translocated elements
    (b) transposable elements
    (c) translocators
    (d) transposons
12. What do eukaryotic genomes contain? (7.6) K/U
    (a) introns
    (b) pseudogenes
    (c) transposons
    (d) all of the above
13. Why is the flu virus considered to be dangerous? (7.7) K/U
    (a) There is no vaccine for it.
    (b) It uses reverse transcriptase to insert its DNA into its host.
    (c) It has a low mutation rate, which makes a vaccine hard to develop.
    (d) It has a high mutation rate, which makes a vaccine hard to develop.

14. Which sequence would form a palindrome? (8.1) K/U
    (a) 5′-TCCGGA-3′
    (b) 5′-CCTGGG-3′
    (c) 5′-TTTCAA-3′
    (d) 5′-CGGGGA-3′
15. What does the Sanger method involve? (8.2) K/U
    (a) using radioactive RNA primers as chain promoters to determine DNA sequences
    (b) using radioactive deoxynucleotides as chain elongators to determine DNA sequences
    (c) using dideoxynucleotides as chain terminators to determine DNA sequences
    (d) using dideoxynucleotides as chain elongators to determine DNA sequences
16. What does the shotgun technique involve? (8.2) K/U
    (a) using computer algorithms to look for overlaps in DNA fragments in order to align them
    (b) using gene guns and computers to fragment DNA that is being sequenced in order to find overlapping sequences
    (c) using multi-beam lasers on DNA fragments in the Sanger method of sequencing
    (d) spreading fragments of a gene between several research labs to sequence them at a faster rate
17. Why did geneticists not explore *E. coli* for insulin production? (8.3) K/U
    (a) Larger organisms are less expensive to grow than *E. coli*.
    (b) Larger organisms can produce larger proteins.
    (c) Larger organisms can produce more complex proteins.
    (d) all of the above

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

18. Fundamental genes are genes that are shared by almost every form of life on Earth. (6.1) K/U
19. Based on her X-ray crystallography results, Franklin determined that the backbone of DNA faced outward. (6.2) K/U
20. Watson and Crick's model of DNA was correct because it solved the issue of consistent width by pairing purines with purines. (6.3) K/U
21. Nucleoside triphosphates aid in DNA replication because they provide both the energy and nucleotides for DNA polymerases. (6.4) K/U
22. Genetic engineering relies on the ability of eubacteria to resist the insertion of foreign DNA. (6.5) K/U
23. Germ-line cells have low concentrations of telomerase, which helps them continually divide. (6.6) K/U
24. rRNA is a structural component of ribosomes and various proteins. (7.1) K/U
25. snRNPs combine with pre-mRNA to form spliceosomes, which are used by eukaryotes to remove introns from pre-mRNA. (7.2) K/U
26. Translation is faster in prokaryotes because transcription can be coupled with translation. (7.3) K/U
27. Alternative splicing produces different combinations of mRNA from the same sequence of pre-mRNA by removing different combinations of introns. (7.4) K/U
28. Induced mutations are caused by inaccurate DNA replication. (7.5) K/U
29. Intergenic DNA is responsible for some gene regulation, but it is currently regarded as non-functional. (7.6) K/U
30. Retroviruses use reverse transcriptase to incorporate their reverse-transcribed double-stranded DNA into the genome of a host cell. (7.7) K/U
31. When working with restriction enzymes, scientists prefer blunt ends to sticky ends because the resulting DNA fragments are easy to join together after treatment. (8.1) K/U
32. The Sanger method requires the use of dideoxynucleotides as chain terminators. (8.2) K/U
33. Canada does not require food that has been genetically modified to be labelled as genetically modified. (8.3) K/U
34. Genetic screening is mandatory for parents with genetic disorders in their families, especially when they are older. (8.4) K/U

Match each term on the left with the most appropriate description on the right.

35. (a) nucleoid
    (b) nucleoside triphosphate
    (c) histone
    (d) purine
    (e) nucleosome
    (f) pyrimidine

    (i) nitrogenous base with a double-ring structure
    (ii) protein that is used in archaea and eukaryotes to condense DNA
    (iii) region in a prokaryote or archaea cell that contains the looped DNA
    (iv) nitrogenous base with a single-ring structure
    (v) building block and energy source of DNA replication
    (vi) unit of DNA storage, which is joined by linker proteins (6.1, 6.2, 6.3, 6.5) K/U

36. (a) mRNA
(b) rRNA
(c) tRNA
(d) sense codon
(e) anticodon
(f) pre-mRNA

(i) contains the anticodon responsible for translation
(ii) found in eukaryotes
(iii) codon sequence similar to that in DNA
(iv) structural component of ribosomes
(v) sequence of base pairs responsible for protein coding
(vi) single-stranded RNA resulting from transcription
(7.1, 7.3, 7.4) K/U

37. (a) dideoxynucleotide
(b) primer
(c) PCR
(d) ethidium bromide
(e) restriction enzyme
(f) molecular marker

(i) fragment of known size that is used in electrophoresis
(ii) process of producing a large number of copies of a DNA fragment
(iii) enzyme that cuts DNA at specific sequences
(iv) complementary sequence for one end of a DNA fragment that is being replicated
(v) used for chain termination in the Sanger method
(vi) base-pair mimic that is used to stain DNA (8.2) K/U

Write a short answer to each question.

38. Explain the importance of Mendel's work to modern molecular genetics. (6.1) K/U

39. What was the problem with Pauling and Corey's model of DNA? (6.3) K/U

40. What do scientists believe is the purpose of telomeres in eukaryotes? (6.6) K/U

41. What traits do germ cells and cancerous cells share? (6.6) K/U

42. What is the importance of the following four codons: AUG, UAA, UAG, and UGA? (7.2) K/U T/I

43. What features of viruses make them good candidates for gene therapy? (7.7) K/U

44. Explain the roles of ethidium bromide and UV light in gel electrophoresis. (8.2) K/U

Understanding

45. Predict what would result from determining the base-pair composition of a piece of RNA, according to Chargaff's rule. Why? (6.2) K/U T/I

46. Explain what is occurring in **Figure 1**. (6.2) K/U

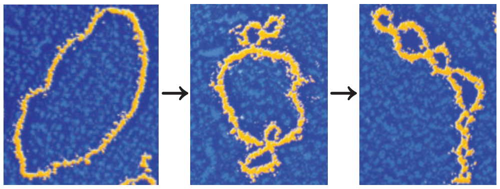


Figure 1

47. Draw the reaction that results in the formation of a phosphodiester bond between two nucleotides. (6.4) K/U T/I C

48. Explain what would occur if each of the following enzymes were absent during DNA replication:
(a) RNA primase
(b) DNA helicase
(c) DNA gyrase (6.5) K/U

49. Explain why condensed chromosomes only exist outside interphase in eukaryotes and what the implications are for the cell. (6.5) K/U T/I

50. Create a table to identify the six differences between the DNA in prokaryotes and eukaryotes. (6.5) K/U C

51. Create a table to organize the types of RNA that are used in transcription and translation. Include their functions and abbreviations, and draw their structures. (7.1) K/U C

52. Many errors can occur during transcription. Using a table, outline the effect that each of the following errors would have on transcription. (7.2) K/U T/I C
(a) The poly(A) tail is not added.
(b) The termination sequence is misread.
(c) The 5′ cap is not added.
(d) The promoter region is not recognized by RNA polymerase.
(e) Exons are excised, rather than introns.

53. **Figure 2** shows a micrograph of an *E. coli* chromosome. Sketch the micrograph in your notebook. Label your sketch, and explain what is occurring. (7.3) K/U T/I

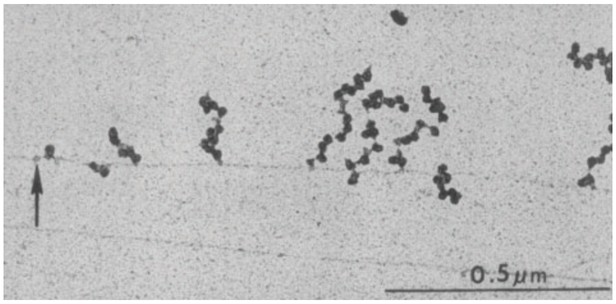


Figure 2

54. Translate the following mRNA sequence into an amino acid sequence, beginning at the start codon: 5′-UUAUUACACGTAAUGUUUCCGCCCUAGCG CCCCGGC-3′(7.3) K/U

55. Compare and contrast the following structures:
    (a) P and A sites
    (b) start and stop codons (7.3) K/U T/I

56. (a) Describe post-translational regulation.
    (b) What are its benefits? (7.4) K/U

57. The *trp* operon is described as repressible, and the *lac* operon is described as inducible. What does this mean for the cell? (7.4) K/U T/I

58. Use the DNA sequence 5′-ATCTCCTGGTAA-3′ to demonstrate the effect of each type of mutation on the resulting polypeptide sequence. (7.6) K/U T/I
    (a) silent mutation
    (b) missense mutation
    (c) inversion
    (d) deletion
    (e) nonsense
    (f) frameshift

59. Describe the importance of pseudogenes in the study of evolution. (7.6) K/U T/I

60. (a) What effect does a restriction enzyme have on a eukaryotic chromosome and a plasmid?
    (b) What does this mean for a research scientist? (8.1) K/U T/I

61. DNA sequencing is a fundamental part of genomics. Explain why DNA sequencing is important and how the Sanger method works. (8.3) K/U T/I

62. If you were a doctor, what would you say to a patient who asked for somatic gene therapy? (8.4) T/I

63. What are the advantages of developing foods (nutraceuticals) that can express genes for medicines? (8.6) K/U T/I

Analysis and Application

64. Hymenopterans (such as bees, ants, and crickets) undergo haplodiploidy for sexual differentiation. Using a diagram, explain how sisters are more related to their mothers than brothers are to their fathers. (6.1) T/I C

65. Imagine that you are examining the condensed genetic material of an organism under an electron microscope. (6.2) K/U T/I
    (a) Describe the structures that you would expect to see if the organism is a eukaryote.
    (b) What structures would you expect to see if the organism is a prokaryote?

66. Which of the following formulas represent Chargaff's findings about the ratios of the nucleotides in a sample of double-stranded DNA? Explain your reasoning. (6.2) K/U T/I
    (a) $A + T + G + C = 1$
    (b) $\frac{(A + G)}{(T + C)} = 1$
    (c) $\frac{(A + C)}{(G + T)} = 1$
    (d) $\frac{G}{C} = \frac{A}{T}$

67. Use your knowledge of DNA replication to create a flow chart of the process. (6.4) K/U T/I C

68. DNA replication in prokaryotes occurs at a rate of approximately 1×10^3 bp/s. If a certain prokaryote requires 57 min to replicate its chromosome, what is the length of its chromosome in millimetres? (6.4) T/I

69. Using a diagram, explain how telomeres lose material as a result of replication. (6.6) K/U T/I

70. **Figure 3** shows the production of compound E. If you were attempting to disable each gene individually using knockout genes, how would you know that you were successful? List your expected results in a table. (7.1) T/I C

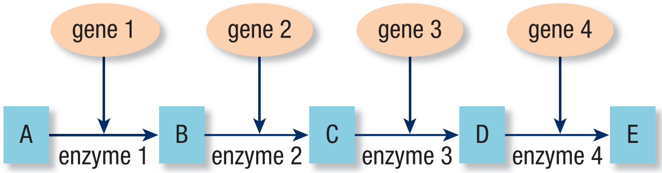


Figure 3

71. Use the codon table (Figure 7 on page 317) to examine the following DNA sequence: CG_CC_CU_UC_GG_GU_AC_ (7.1) K/U T/I
    (a) Why can there be blanks in this sequence?
    (b) Why is this sequence a good example of the wobble hypothesis?

72. The protein ubiquitin is small, with only 76 amino acids. The protein titin has 34 350 amino acids. (7.3) K/U T/I C
    (a) A eukaryote can synthesize a protein at a rate of 6 aa/s (amino acids per second), and a prokaryote can synthesize a protein at a rate of 17 aa/s. How much longer would it take a eukaryote to synthesize ubiquitin and titin than a prokaryote?
    (b) What is the main reason for the different rates?

73. Use a t-chart to describe the key differences in translation in prokaryotes and eukaryotes. (7.3) K/U T/I C

74. While investigating a new protein that could be used to fight cancer, you isolate bacteria that produce the protein. You know that there are four enzymes in the pathway used by the bacteria to produce the protein. You also know that the bacteria rely on specific substrates to produce the protein. To investigate the pathway, you establish several experimental conditions. All but one of these conditions result in the protein being produced. Use your observations in **Table 1** to draw the pathway. (7.1) K/U T/I C

Table 1

Substrate removed	Product from enzyme 1	Product from enzyme 2	Product from enzyme 3	Product from enzyme 4
1	present	present	absent	absent
2	present	absent	absent	absent
3	present	present	present	present
4	absent	absent	absent	absent
5	present	present	present	absent

75. Suppose that you are investigating the effects of mutating the *lac* operon in *E. coli*. One mutation causes the synthesis of β-galactosidase, despite the presence or absence of its inducer. What does this mean for the cell? Explain. (7.4) K/U T/I A

76. Centromeres and telomeres contain many repetitive sequences. (7.6) K/U T/I A
    (a) Why would this be an advantage for the cell?
    (b) Would you expect exons to be in the telomeric and centromeric regions?

77. The human genome has a mutation rate of 2.7×10^{-8} bp per generation. The DNA in our mitochondria has a mutation rate of 2.7×10^{-5} bp per generation. (7.5) K/U
    (a) How much faster are our mitochondria mutating than our genome?
    (b) Mitochondrial DNA contains about 2.5×10^{6} bp. How long would it take to substitute all the present base pairs? Assume that each generation is 20 years.
    (c) The human genome contains about 3×10^{9} bp. How long would it take to substitute all the present base pairs? Assume that each generation is 20 years.
    (d) Explain how the high mutation rate might account for the endosymbiotic theory.

78. Construct a restriction map using the information in **Table 2**. (8.1) K/U C

Table 2

BamIII	EcoRI	EcoRI+BamIII
600 bp 600 bp 1400 bp	300 bp 2300 bp	100 bp 200 bp 500 bp 600 bp 1200 bp

79. (a) Describe the technique of nanopore sequencing.
    (b) Why does nanopore sequencing promise to be the gene-sequencing method of the future? (8.2) K/U T/I

80. (a) How does the technology represented by DNA microarrays do more for scientists than just locate specific genes?
    (b) Explain the significance of the capabilities of DNA microarrays. (8.2) T/I A

81. Suppose that you are working in a laboratory and the labels have fallen off two of your cell cultures. You know that one culture has normal cells and the other culture has cancerous cells. What technology could help you distinguish them? (8.3) T/I

Evaluation

82. To examine Okazaki fragments, Pauling and Hamm used two strains of *E. coli*. The DNA ligase of one strain functioned optimally below 40 °C, and the DNA ligase of the other strain functioned optimally above 40 °C. Pauling and Hamm incubated the two strains separately, starting at 25 °C. Then they raised the temperature to 40 °C and added radionucleotides. (6.4) T/I
    (a) What do you think were their predicted observations? Explain.
    (b) Explain why the two strains were incubated at 25 °C first.
    (c) What would be labelled with the radionucleotides?
    (d) What conclusion do you think Pauling and Hamm made from their observations?

83. DNA polymerase functions as an exonuclease, working with ligase to repair incorrect nucleotide sequences during DNA replication. How could this be used to treat diseases such as cystic fibrosis, which is a point mutation? (6.4) K/U

84. Prokaryote DNA replicates at a rate of roughly 1000 bp/s. Eukaryote DNA replicates at a rate of roughly 50 bp/s. (6.5) T/I
    (a) Based on this information, would you predict that the rate of DNA replication in archaea would be closer to the rate for prokaryotes or the rate for eukaryotes? Explain.
    (b) Actual DNA replication in archaea occurs approximately 10 times as fast as it does in eukaryotes. What implication does this have for including archaea in their own domain?

85. Defend the argument that the wobble hypothesis protects the integrity of the genetic code and allows for flexibility at the same time. (7.1) K/U T/I

86. As a graduate student, you have identified a human gene that codes for a cellular senescence in cancerous cells. Excited, you quickly isolate the gene and insert it in *E. coli* to study the protein. Unfortunately, when you insert the protein into HeLa cells (a cancerous perpetual cell line), the cells continue to divide. Your adviser tells you to look at your procedure before you run another set of experiments. What does your adviser want you to change? (7.2) K/U

87. In genetic experiments, the *lac*, *amp*, *ara*, and *trp* operons are sometimes inserted individually or in combination with each other, along with another gene under investigation. Why would molecular geneticists add one of these sequences? (7.4) K/U

88. Many people get a flu vaccine once a year. In Canada, children are given one measles vaccine, plus a booster, and only one polio vaccine. However, a highly effective HIV vaccine remains elusive. Develop a hypothesis that might explain this discrepancy in our ability to develop an HIV vaccine. (8.1) K/U T/I

89. Scientists have discovered the gene for spider silk protein. They have isolated this gene and are looking for a host organism to produce it. Would you choose a goat or a tobacco plant as the host organism? Defend your choice. (8.3) K/U A

90. A strain of strawberries with a fish antifreeze protein from trout has been developed to prevent the strawberries from freezing. Construct an argument that would defend or refute the commercial use of this organism. (8.4) K/U T/I

91. You have been hired by the Canada Border Services Agency in their animal protection division. You know that komodo dragons are a CITES I species, which makes their trade from wild populations illegal. A shipment of komodo dragons arrives with papers indicating that they are captive born and can be traded (**Figure 4**). Since all captive-born komodo dragons come from a small population, they share much of their DNA. Use **Figure 5** to answer the following questions. (8.2) K/U

Figure 4

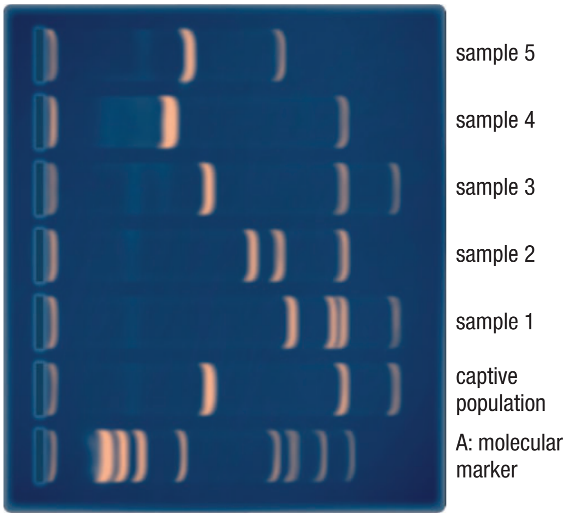


Figure 5

(a) What is the purpose of lane A?
(b) What can you infer about the shipment of komodo dragons?
(c) If this sequence was performed with variable number tandem repeats (VNTRs), how could it be improved? Why?
(d) How do you think molecular genetics has helped to limit the illegal animal trade?
(e) How could DNA microarray technology help to limit the smuggling of animals and animal products?

Reflect on Your Learning

92. Draw a concept map to show the links between the three chapters in this unit. K/U C

93. Given the current state of gene therapy, would you consider it for treating a relative or friend with a genetic disease? Why? K/U T/I

94. Should all Canadians submit a DNA sample to a database in case of a natural or human-made disaster? How would your answer change if the database were to be used to prosecute criminals? How would it change if the uses of the database were not yet determined? How do you think our genetic rights should be protected, or should we have genetic rights? K/U T/I A

95. How has molecular genetics changed our world? What ethical and legal issues are associated with molecular genetic technologies? How has this unit changed your opinion of these technologies and science in general? T/I A

96. What have you learned about major scientific discoveries and how they occurred? K/U T/I

Research

WEB LINK

97. Krastan B. Blagoev studied the role of telomerase during the early development of cell lines. He discovered that he could block telomerase using an inhibitor. His results are shown in **Figure 6**. K/U T/I

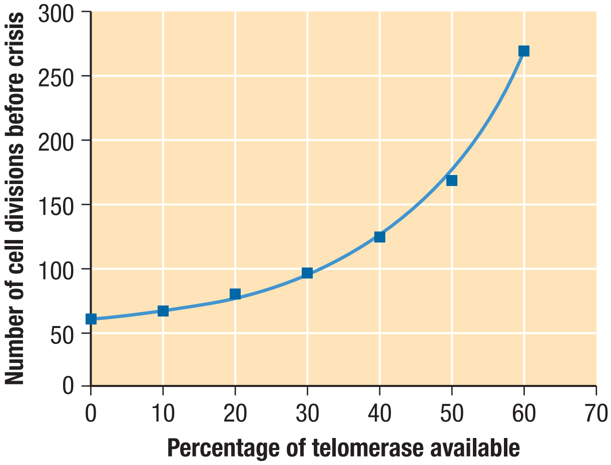


Figure 6

(a) What conclusions can you make from Blagoev's findings?

(b) How might his findings affect cancer treatment? (Telomerase inhibition appears to be lacking in cancer cells.)

(c) Read about his research, and compare your conclusions with his.

98. Fundamental genes are ubiquitous throughout a great variety of organisms. Some scientists have argued that the *Hox* gene is the most fundamental of all genes. It controls the segmentation of deuterostome organisms (**Figure 7**). Prepare an Internet profile page for the *Hox* gene, which has set its status as "fundamental gene." Post your thoughts about its new status on its wall. Make sure that you include answers to the following questions in your posting:

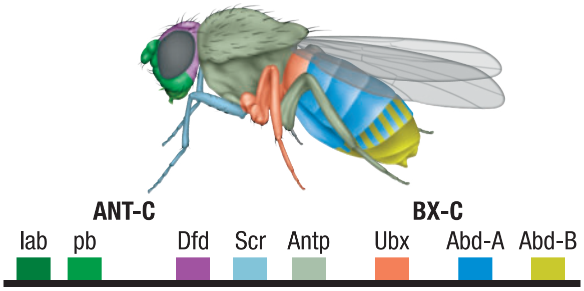


Figure 7 In this diagram, the location of the *Hox* gene responsible for the proper development of the segment is matched with the segment it controls. Notice that the segments are in the same order as their genes.

- Where is the *Hox* gene located, and what does it do?
- What is another name for this type of gene? Why?
- Does the *Hox* gene vary between evolutionary groups?
- Does the *Hox* gene function the same way in all organisms?
- How has the *Hox* gene allowed for the development of evolutionary developmental (evo-devo) biology? K/U T/I

99. Rapid sequencing of a genome played a large part in completing the Human Genome Project. It is now the focus of the Archon genetics X-prize. The Archon X-prize is offering $10 million to the scientists who develop a fast and inexpensive sequencing technique to sequence the whole human. Like on television, every police investigation or medical test could begin with a DNA sample and rapid sequencing. T/I C A

(a) Prepare a poster or short informative pamphlet about rapid sequencing and the myths and truths that surround this technology.

(b) Compile a timeline that shows the development of rapid-sequencing technologies. Include a brief description of the pros and cons of each technology.

(c) Investigate the use of rapid sequencing in crime analysis. Explain why all cases do not have DNA collected or evaluated.

100. In many ways, our present knowledge of cancer can be attributed to Henrietta Lacks and George Otta Gey. However, their roles and contributions to science have not been without controversy. Legal battles, cold-war drama, worldwide cell-line contamination, a novel, and the attempt to classify a human cell as a paraphyletic species give their story many interesting facets. Their story involves one of the most important research tools that medical science has ever had, with over 60 000 papers already published and over 3000 more written every year. In a mixed media or written format, prepare a summary about the HeLa cell line and its variants. Include answers to the following questions:
    - Who were Henrietta Lacks and George Otta Gey?
    - What are HeLa cells? How were they collected?
    - What modification makes the HeLa cell line important to medical research?
    - What are the legal and ethical controversies that have followed this cell line?
    - Is this cell line truly its own species? T/I
101. With the advent of personal computers and gaming systems, as well as the proliferation of high-powered processors in many personal computers, scientists are increasingly able to harness public expertise to solve complicated computational problems. Fold-it is just one example of how this relationship can work. As you have learned, proteins fold in very specific ways, which are still a mystery to scientists. Fold-it asks gamers to take an amino acid chain and attempt to fold it in the right way to form a protein. In a brief report, research how crowdsourcing (using a large crowd to perform tasks usually accomplished by an individual) has changed proteomics and bioinformatics. Include answers to these focus questions in your report:
    - What is crowdsourcing? Do scientists still need people with a game system to solve problems in science?
    - Does crowdsourcing reduce problems in science to little more than trivial games?
    - What are some other examples of bioinformatics and proteomics being crowdsourced? T/I
102. RNA is a very diverse molecule. Not only can it code genetic information, but also it can act like a protein. Scientists are only starting to understand many of its interesting characteristics and features. Prepare an argument to support the position that RNA is more important than DNA in the evolution of life on Earth. Be sure to include the following information:
    - a t-chart that outlines the types of RNA and DNA and their functions
    - where RNA and DNA are found on the tree of life
    - how the chemistry and molecular structure of RNA allow it to have such a varied role T/I C A
103. Pseudogenes are regions of DNA that have many gene-like features but do not function. In one sense, they can be considered excess DNA, or even "junk DNA." However, research indicates that they may play a role in immunity and evolution. Prepare a poster or pamphlet to raise awareness of pseudogenes and argue against the use of the term "junk DNA." Include the following information in your poster and pamphlet:
    - the types and origins of pseudogenes
    - whether pseudogenes are truly non-functional
    - how pseudogenes are used by the cells
    - how new findings about pseudogenes may help evolutionary biologists T/I C A
104. Vaccines have become a contentious issue around the world, partly due to bad, non-reproducible science. Risk reports are mathematical models that relate the apparent risk of two situations, such as the risk of contracting a disease versus the risk of having an adverse reaction to the vaccine. T/I C A
    (a) Prepare a risk report that compares the mortality rate for the measles or mumps vaccine versus the mortality rate from measles or mumps without the vaccine.
    (b) How have bad science and the media endangered our present society?
    (c) What has happened around the globe as a result of people not receiving the measles and mumps vaccines?
105. Many people argue that using genetically modified organisms, such as knockout mice, for research is unethical. Yet this has led to major advances in diagnostic and clinical medicine. One such advancement is new understanding of the *FoxP2* gene. Research and answer the following questions. T/I
    (a) How have knockout mice played a role in the discovery of the function of the *FoxP2* gene?
    (b) How conserved is the *FoxP2* gene? How can you interpret this information for evolutionary purposes?
    (c) What other transgenic organisms have been developed for commercial purposes?
    (d) Choose one of the GMOs from (c), and research its development.
106. Genomics, functional genomics, structural genomics, and proteomics are areas of research that are changing the way that medicine is conducted. Suppose that you have been asked to lead a class about molecular genetics, focusing on the future of research. Design a multimedia presentation that differentiates these four areas of research and their goals, as well as the technology involved in molecular genetics. T/I C A

UNIT 4

Homeostasis

OVERALL EXPECTATIONS

- evaluate the impact on the human body of selected chemical substances and of environmental factors related to human activity
- investigate the feedback mechanisms that maintain homeostasis in living organisms
- demonstrate an understanding of the anatomy and physiology of human body systems, and explain the mechanisms that enable the body to maintain homeostasis

BIG IDEAS

- Organisms have strict limits on the internal conditions that they can tolerate.
- Systems that maintain homeostasis rely on feedback mechanisms.
- Environmental factors can affect homeostasis.

UNIT TASK **PREVIEW**

In the Unit Task, you will explore an environmental stimulus that affects homeostasis. The Unit Task is described in detail on page 566. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

THE MORE THINGS CHANGE, THE MORE THEY STAY THE SAME

While Canada enjoys a plentiful supply of clean fresh water, other countries are not so fortunate. Many parts of the world suffer from a lack of water and a severe shortage of potable water. After witnessing the clean water crisis in Africa, Canadian endurance runner and activist Ray Zahab decided to raise awareness of this serious problem. In November 2006, he and his team set out to run across the Sahara Desert.

Averaging over 62 km per day for 111 straight days, Ray's expedition faced some of the most gruelling conditions found anywhere on the planet. Temperatures in the Sahara can range from 0 °C at night to 50 °C during the day. To beat the intense heat, Ray had to wake at 4 a.m. every day to start running by 5 a.m. Besides worrying about possible dehydration and heat stroke, Ray had to deal with other unexpected health issues as well. He was infected with a severe intestinal virus and also developed tendonitis, which almost ended the expedition early. The 7500 km expedition required years of training, incredible dedication, and a precise knowledge of how the human body responds to extreme conditions. A huge amount of preparation, such as endurance training, was required to strengthen the muscular, skeletal, respiratory, and circulatory systems. Proper nutrition and hydration, and adequate rest for optimal functioning were also required.

The conditions of the external environment are just as important as the conditions inside our bodies. During an expedition such as the one that Ray undertook, the body experiences severe physical stresses. Our bodies have many ways to deal with these stresses to maintain optimal functioning. When we undergo intense physical activity, our cells require additional oxygen to burn glucose and release energy. Our body's response is to increase our breathing and heart rates to meet this oxygen demand. Our blood flow increases to carry the additional oxygen to all of our tissues. When our body temperature increases, our body responds by sweating to cool itself down. Sweating leads to a loss of body fluids, which can have an adverse effect on blood sugar levels and blood pressure. The body then increases its production of the hormones insulin and glucagon, which act to regulate blood sugar. Excessive sweating also leads to the release of hormones that limit water loss through the excretory system.

All of these systems enable the body to maintain an internal balance. Cells, tissues, organs, and body systems function as efficiently as possible only when they enjoy the right conditions. In this unit, you will learn about the many systems that maintain the delicate and continuous balance within the human body.

Questions

1. Summarize the various stresses that the human body undergoes in such extreme conditions.
2. What might be some of the consequences if the body could not respond to these stresses?
3. What are some other stresses that the body commonly goes through?
4. Do you think an expedition such as Ray Zahab's is an effective way to raise awareness of serious social or environmental problems around the world? Explain your answer.

UNIT 4 ARE YOU READY?

CONCEPTS

- recognize that cells exchange materials with their surroundings by passive and active transport
- understand that many cellular processes are controlled by feedback mechanisms
- know that the interdependence of body systems is essential for proper functioning of an organism
- identify the hierarchy of tissues, organs, and organ systems in which the cells in the body are arranged
- understand that substances move into and out of the cells by diffusion (for solutes) and osmosis (for water)
- know that organ systems work together to meet the needs of an organism
- understand that organisms must be able to respond to changes in their environment

SKILLS

- identify a testable question
- identify dependent, independent, and controlled variables
- collect, analyze, and interpret observations
- identify potential safety issues in a laboratory
- measure temperature, heart rate, and blood pressure with appropriate instruments
- identify errors in experimentation
- create hypotheses from provided, found, and collected data

Concepts Review

1. (a) Describe the concept of a concentration gradient.
   (b) How does this concept relate to how a cell maintains its internal environment? K/U
2. (a) Explain what would happen if an animal cell were placed in a hypertonic solution.
   (b) Explain what would happen if an animal cell were placed in a hypotonic solution. K/U
3. Decide whether **Figures 1** and **2** depict osmosis or simple diffusion. Explain your decisions. K/U

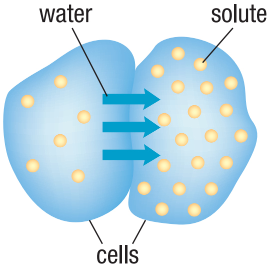


Figure 1

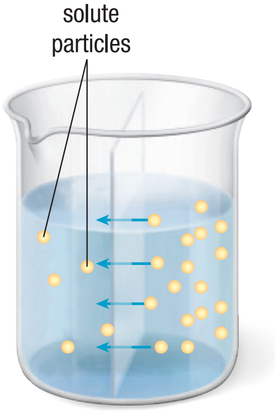


Figure 2

4. Describe how the respiratory and circulatory systems work together to provide the body with oxygen. Draw a simple diagram to illustrate your description. T/I C
5. Describe the function and role of a sweat gland. K/U
6. (a) List three organ systems within the bodies of mammals.
   (b) Describe how these three systems interact with one another, if at all. K/U
7. Match each organ in the left column with its regulatory function in the right column. (Remember that a regulatory function can be linked to more than one organ, and an organ can have more than one function.) K/U
   (a) heart
   (b) pancreas
   (c) kidneys
   (d) stomach
   (e) intestines
   (f) liver
   (g) lungs
   (i) regulate oxygen levels
   (ii) break down food
   (iii) digest nutrients
   (iv) filter bodily fluids
   (v) maintain blood sugar
   (vi) maintain blood pressure
   (vii) prevent disease
8. An animal sees a predator approaching. It assesses the situation and decides to flee. K/U
   (a) Describe how the animal's nervous system is involved in this scenario.
   (b) Describe how the animal's muscular system is involved in this scenario.
9. Describe three ways that animals cope with below-zero temperatures. K/U
10. Describe a time when you had not eaten for awhile. What feelings did you have, and what do you think caused these feelings? K/U

11. As a patient was admitted to an emergency room, her blood pressure was measured as 155/95. K/U T/I
    (a) What do these two numbers represent?
    (b) Is this blood pressure normal? Why or why not?
    (c) Suggest some possible reasons why the patient has this blood pressure.
12. On a hot day, suppose that you bask in the sunlight and sweat. Can you assume that your body is overheated and in danger of heat stress? Why or why not? T/I
13. Organs are classified into organ systems according to their anatomy or physiology. Distinguish between anatomy and physiology. K/U
14. The human body contains multiple levels of structural organization. Put the following levels of complexity in the correct order from smallest to largest and give an example of each: cells, systems, atoms, organism, tissues, molecules, organs, organelles. K/U
15. (a) What are body tissues?
    (b) How many types of tissues are there?
    (c) What makes one type of tissue different from another type of tissue? K/U
16. Give an example of an organ that performs functions in more than one body system. Include in your answer all body systems in which the organ is active. K/U
17. Compare and contrast passive and active transport. K/U
18. Suggest two ways in which osmosis and diffusion are the same and two ways in which they are different. K/U
19. How is the rate of diffusion affected by each of the following? K/U
    (a) a change in temperature
    (b) a change in the concentration gradient
20. Why do you think that eating salty foods makes your lips feel dry? K/U T/I
21. How do endocytosis and exocytosis differ? K/U
22. If you could use only one word to explain the concept of homeostasis, which word would you choose? K/U C
23. What is the normal level for the average adult human body at rest for each of the following functions? K/U T/I
    (a) body temperature
    (b) heart rate
    (c) breathing rate

Skills Review

24. At various points during this unit, you will be asked to conduct research on the Internet. What criteria will you use to determine whether or not a website is reputable? T/I
25. During an experiment, the participants ate different foods. Their blood glucose levels were measured afterwards. The results of the experiment are recorded in **Table 1**. T/I

Table 1

Food consumed	Blood glucose 30 min later (m·mol/L)
none (fasting)	3.5
apple	4.5
white bread	6.2
ice cream	5.9
lentils	4.2
corn flakes	6.6

    (a) What are the independent and dependent variables in this experiment?
    (b) What may have been the testable question for this experiment? What may have been the hypothesis?
    (c) If you graphed the data obtained in this experiment, what variable would you put on the *x*-axis? What variable would you put on the *y*-axis?
    (d) Suppose that each food was consumed by a different participant. How might this influence the validity of the experiment?
    (e) How could this experiment be done to include a control?

CAREER PATHWAYS PREVIEW

Throughout this unit you will see Career Links. Go to the Nelson Science website to find information about careers related to homeostasis and physiology. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 9

Homeostasis: A Fine Balance

KEY CONCEPTS

After completing this chapter you will be able to

- describe how organisms maintain internal conditions that are suitable for life and for responding to stress
- understand that homeostasis is the physiological condition that enables an organism to adjust to its external environment
- describe negative feedback systems and how they allow organisms to maintain internal conditions that are suitable for life processes
- describe the excretory system and how its primary organ, the kidney, works to eliminate waste from the body and maintain water balance
- explain how some organisms thermoregulate in response to hot and cold stresses
- understand how homeostasis can be affected by infection and disease

How Do Animals Maintain an Internal Balance?

All organisms have preferred environments, but they can live in a tolerable range of environmental conditions. Animals sweat, seek shade, or shiver to control thermal energy; plants open and close stomata in their leaves to control water loss through transpiration; and bacteria can adjust their cell walls to accommodate less desirable conditions. Most animals cannot control their surroundings, so they live in environments with appropriate physical conditions. Humans, on the other hand, have mastered the ability to change their surroundings, so they can live in almost any climate on Earth. For example, temperatures in northern Ontario can reach above 30 °C in the summer, causing people to sweat and seek shade or air-conditioned areas to cool themselves. In the winter, however, people in northern Ontario can experience dangerously low temperatures, below −35 °C.

Aside from location and physiological adaptations, an organism's survival ultimately depends on its ability to maintain its internal environment. Specifically, body cells must be able to replicate, communicate, and metabolize effectively for life to continue. In Unit 2, you learned about the metabolic processes that occur within our cells. In this chapter, you will learn about the conditions that are necessary for these processes to continue.

One of the most critical factors for maintaining proper cell function is temperature. The metabolic processes that are carried out by the cells can only successfully occur within a fairly narrow range of temperatures. The cells in the human body require an internal temperature of roughly 37 °C, which is normal body temperature. Even relatively small variations from this temperature can have damaging or deadly effects. A sustained body temperature below 35 °C or greater than 37.8 °C can cause some bodily processes to malfunction. The human body has many mechanisms that regulate its internal temperature. When we get too hot, we sweat. When our body temperature drops, we shiver to produce thermal energy. Most animals have physiological or behavioural adaptations that allow them to maintain a suitable temperature.

The external environment affects the body's internal conditions, and the body must adjust to ensure that it functions efficiently. In this chapter, you will study the mechanisms that organisms use to regulate internal temperature and proper water volume and content in a constantly changing environment.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Both aquatic and terrestrial animals must maintain appropriate water content in order to survive, but how they do this may differ. How do terrestrial animals maintain suitable water concentrations? How do you think aquatic animals maintain suitable water concentrations?
2. Reflect on the last time you experienced overheating or the last time you felt very cold.
   (a) What are the dangers of being too hot or too cold? Do you think one is more dangerous than the other? Explain your answer.
   (b) How did you and your body respond to the temperature extreme you experienced? Were the responses all physiological, all behavioural, or a combination of both? Explain.

Mini Investigation

Modelling Temperature Control

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK **A1.2, A2.1, A5.4**

In this activity, you will model temperature control. You will use a source of thermal energy and a cooling mechanism to regulate the temperature of a container of water and attempt to maintain a constant temperature.

Equipment and Materials: 2 beakers (1 small and 1 large); 2 alcohol thermometers or temperature probes; stands and clamps to hold beakers and thermometers; wire gauze; Bunsen burner or other source of thermal energy; stirring rod; water; crushed ice

1. Add 200 mL of water to the small beaker. Secure the beaker and the thermometer. Ensure that the bulb of the thermometer does not touch the bottom of the beaker.
2. Use the Bunsen burner or another source of thermal energy to bring the temperature of the water to 60 °C. When the water reaches this temperature, remove the energy source.
3. If the temperature rises above 62 °C, add crushed ice. If the temperature falls below 58 °C, reheat the water.
4. Observe and record the temperature every 30 s for 5 min.
5. Add 50 mL of water to the small beaker.
6. Repeat Steps 2 to 4.
7. Add 200 mL of water to the large beaker.
8. Repeat Steps 2 to 4 again.
9. Plot the data from all three setups on a single graph.

A. Were you able to maintain a constant temperature? Explain your answer. T/I

B. If the source of thermal energy were applied continuously, what would you need to do to maintain a constant temperature? T/I

C. Explain how volume affected your ability to maintain a constant temperature. T/I

D. Does surface area have any effect on the cooling rate of the water? Explain. T/I

E. How does this investigation relate to temperature control in the human body? T/I

F. What are the strengths and weaknesses of this investigation as a model of temperature control in the human body? T/I

9.1 Maintaining an Internal Balance

You learned in the unit opener that Ray Zahab endured great physical strain as he raced across the extreme environment of the Sahara Desert. However, there are many animals native to the Sahara Desert that thrive in these conditions using special adaptations. One example is the fennec fox (*Vulpes zerda*) (**Figure 1**). Its enormous ears serve two important functions that enable it to live in such a hostile habitat. First, the large ears enhance its hearing. This allows it to hear predators coming from far away, as well as hear prey, even when underground. The large ears also act as "radiators." As you learned in the Mini Investigation in the chapter opener, the greater the surface area is, the faster and more easily the temperature can be regulated downward. The fennec fox's radiator ears give it a large surface area to dissipate thermal energy faster. Maintaining an optimal internal temperature helps the fennec fox thrive in temperatures that range from below 0 °C to above 50 °C. The maintenance of the body's internal conditions is called homeostasis. In this unit, you will be examining homeostasis in animals.

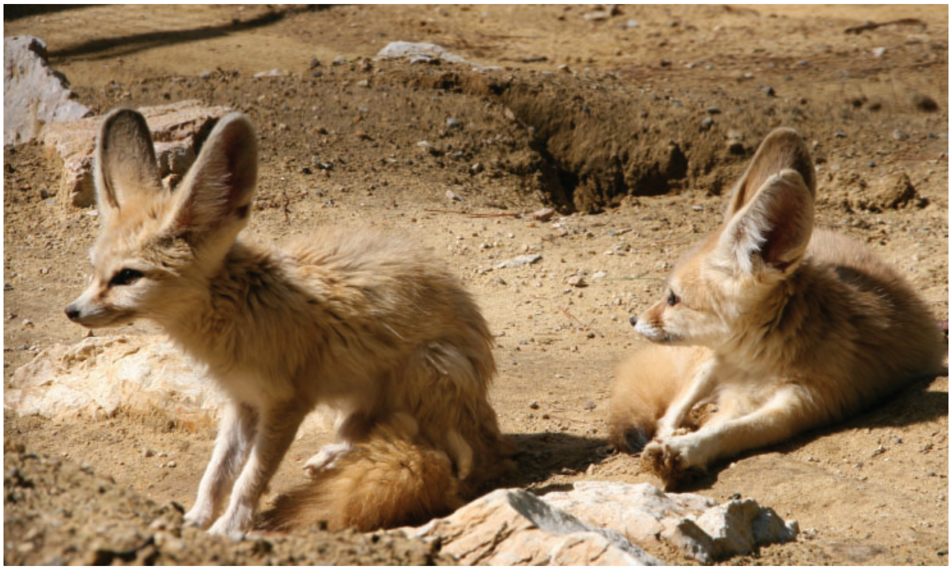


Figure 1 The large ears of a fennec fox act as "radiators" to dissipate thermal energy in the hot Sahara Desert.

homeostasis the physiological state of the body in which internal physical and chemical conditions are kept within a range that is suitable for life processes

Homeostasis is the physiological state of the body in which the internal physical and chemical conditions are maintained within an acceptable or tolerable range that is suitable for essential biological processes. Homeostasis is not a "steady state" or a constant condition, but rather a dynamic process that is continuously adjusted in response to changes in the internal or external environment. For example, the body must maintain its optimal range of conditions during exercise, fatigue, and extremes of temperature.

Imagine the body's internal conditions as a car engine that can never be turned off. The engine must be constantly fuelled to run properly. It may need to have coolant and oil added occasionally to maintain its proper operating conditions. Sometimes, parts such as the alternator need to be replaced to recharge the batteries. Like the human body, a car engine also has several built-in diagnostic tools. These tools, such as the thermostat and computer, are used to address any issues that may impede proper operations. When the negative issues are addressed, proper operations can be restored.

Similarly, the body has several key parts, fluids, and conditions that must be monitored and adjusted for the body's homeostasis, or proper operations, to be maintained. These include internal temperature; hormone levels; and the pressure, pH, flow, and concentration of glucose and other solutes in the blood. For some factors, such as the blood pH and internal temperature, the tolerable range is fairly narrow. In others, such as blood flow, glucose levels, and hormone levels, the tolerable range is broader and there can be considerable variation without harmful consequences.

In this section, you will explore answers to the following questions: What is homeostasis? What does "internal balance" really mean? What body systems are involved in maintaining this balance?

The Internal Environment

The purpose of homeostasis is to maintain internal physical and chemical conditions that are appropriate for the cells to function properly. The **internal environment** refers to the extracellular fluid, which consists of the **interstitial fluid** that fills the spaces between our cells and tissues, and the plasma or fluid portion of our blood. A typical adult has 15 L of extracellular fluid, which constitutes approximately 20 % of our body's mass. When discussing homeostasis, we do not include the intracellular fluid (the fluid inside of the cells). Instead, we focus on the fluid outside of the cells.

internal environment the extracellular fluid, which consists of the fluid that surrounds the cells and tissues in the body and the plasma portion of the blood

interstitial fluid the fluid that surrounds the body cells

Every cell in the body is surrounded by the extracellular fluid, which acts as a medium for delivering energy, transporting chemicals, and eliminating waste. The regulated flow of energy, chemicals, and waste into and out of the extracellular fluid allows the cells to function properly. When the cells function properly, the tissues, organs, and organ systems, and thus the whole organism, can thrive.

The volume, temperature, and chemical composition of our internal environment can change quickly. Rigorous physical activity, other extreme conditions, and even infection can tip the balance that is maintained in the extracellular fluid. These changes can have a dramatic (often negative) effect on cellular functions, so the body uses many systems to maintain and regulate its internal conditions. CAREER LINK

Organ Systems Involved in Homeostasis

Establishing and maintaining homeostasis requires the work of a complex set of activities and processes. There are numerous organs and organ systems that are directly involved in homeostasis (**Figure 2**).

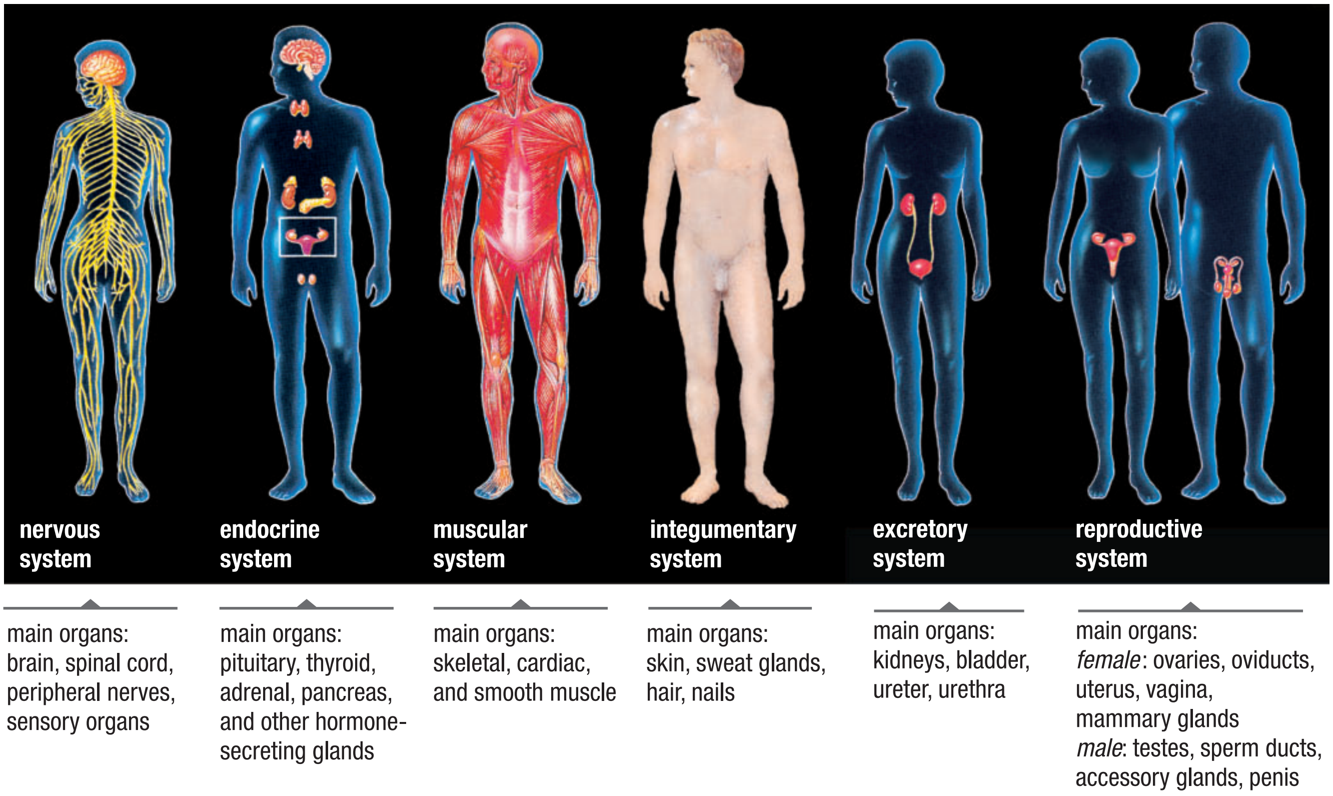

nervous system
main organs: brain, spinal cord, peripheral nerves, sensory organs
endocrine system
main organs: pituitary, thyroid, adrenal, pancreas, and other hormone-secreting glands
muscular system
main organs: skeletal, cardiac, and smooth muscle
integumentary system
main organs: skin, sweat glands, hair, nails
excretory system
main organs: kidneys, bladder, ureter, urethra
reproductive system
main organs: *female*: ovaries, oviducts, uterus, vagina, mammary glands *male*: testes, sperm ducts, accessory glands, penis

Figure 2 This diagram shows some of the organ systems in the human body. All of the organ systems play a role in maintaining homeostasis in the internal environment.

The nervous system (Chapter 11) receives sensory data from the environment, which informs the body of external conditions and transmits signals throughout the body to regulate homeostasis. The excretory system (Section 9.5) works to rid the body of waste and maintain a clean internal environment. The endocrine system (Chapter 10) regulates the levels of various hormones that are essential to life processes, and the circulatory system carries these hormones and other chemicals throughout the body and distributes thermal energy. The immune system protects the body from infection and also fights infection. The liver—an organ that is part of the digestive system—has several roles in maintaining homeostasis. For example, the liver controls amino acid levels by breaking down any amino acids that are not used, detoxifying harmful chemicals (such as alcohol), and manufacturing important blood proteins. The integumentary system, or skin, is important for maintaining a constant body temperature, since it is in constant contact with the external environment.

The cells within these tissues and organs carry out basic metabolic activities that contribute to the function of each organ system as a whole. All of the organ systems are coordinated to carry out the tasks necessary for the survival of the organism. No matter how simple or complex the animal, these functions include

- taking in nutrients and other required chemicals (such as oxygen) from the environment, processing and distributing them throughout the body, and disposing of the waste
- synthesizing proteins, fats, carbohydrates, and other molecules that are essential for cellular function and structure
- sensing and responding to changes in the external environment, such as temperature, physical sensations, and pH
- protecting the body from injury and from infection by viruses, bacteria, and other disease-causing agents
- reproducing, and protecting and feeding offspring

Together these tasks maintain homeostasis within the body. Their functions and activities make up most of an animal's actions during its life, because maintaining an internal dynamic equilibrium is the only way that life can continue.

The endocrine and nervous systems are the most important systems for maintaining homeostasis. (You will study these systems in detail in Chapters 10 and 11.) For example, oxygen and carbon dioxide concentrations are regulated by the nervous system, blood glucose is mainly regulated by the endocrine system, and blood pH and internal temperature are regulated by both systems. These are only a few of the many **homeostatic mechanisms** that are responsible for maintaining homeostasis by responding to changes in either the internal environment or the external environment. To understand how homeostatic mechanisms work, consider the regulation of body temperature. When the body's internal temperature is too high, we sweat; the evaporation of sweat from our skin is an endothermic process, so the body experiences a net loss of thermal energy absorbed by the water during this change of state. When we are cold, we shiver; these tiny muscle contractions generate thermal energy and raise the internal temperature. Even the sensations of hunger and thirst are mechanisms that trigger behavioural responses to ensure the adequate nutrition and hydration of an animal.

homeostatic mechanism a system that monitors internal and external conditions and changes bodily functions to maintain homeostasis

Since homeostatic mechanisms respond to internal and external conditions, they are described as detection-correction or feedback systems. In the next section, you will take a closer look at how the elements of homeostatic mechanisms use information about internal or external conditions to maintain homeostasis.

9.1 Review

Summary

- Homeostasis is the process by which animals and plants maintain an internal environment that promotes proper cellular function.
- Homeostasis is an ongoing dynamic process that acts in response to both internal and external conditions.
- The body's internal environment consists of the interstitial fluid that surrounds cells and tissues, and the plasma in the blood.
- Numerous organs and organ systems coordinate their activities to maintain homeostasis; however, the nervous and endocrine systems are the most important systems.

Questions

1. Explain the meaning of homeostasis, and give an example of how homeostasis occurs in the body. K/U
2. Why is homeostasis not considered to be a "constant" condition? Be specific in your response. K/U
3. List the body's responses to being too hot or too cold. What are some of the organ systems that may be involved in these responses? K/U
4. Suggest some situations in which it may be better if the body does not maintain homeostasis. (Think of specific chemicals or conditions within the body.) A
5. Diabetes, a disease that disrupts the blood glucose homeostasis, can be lethal if not monitored and maintained. Research and describe how humans artificially maintain their blood glucose levels. 🌐 T/I
6. In the car analogy, there were several examples of diagnostic tools that the car uses to maintain homeostasis (**Figure 3**). What are some examples of diagnostic tools in the body? K/U

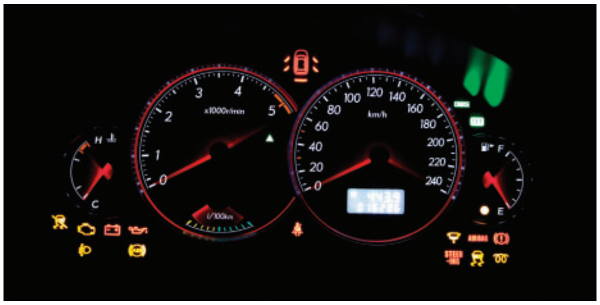


Figure 3

7. Explain how cruise control on a vehicle is a good metaphor for homeostasis. K/U A
8. The fennec fox is a member of the dog family (*Canidae*) (Figure 1, page 428). 🌐 K/U T/I
    (a) Using the Internet and other resources, research how other members of the dog family maintain temperature homeostasis.
    (b) Does what you have learned about the fennec fox provide you with any insights about the size and shape of an elephant's ears? Explain.
9. Why does the body sometimes go outside normal homeostasis ranges? T/I
10. Certain molecules in the muscular system must be maintained in a homeostatic range for the muscles to operate properly. What symptoms might indicate that these molecules are outside of the normal range? T/I
11. Explain the relationship of the terms "regulation" and "feedback" to the concept of homeostasis. K/U
12. Every year some deaths are linked to vigorous exercise or exertion in hot, humid conditions. What are the body's homeostatic mechanisms for heat and humidity? Why do you think these mechanisms do not always work? K/U T/I

🌐 WEB LINK

9.2

Homeostasis and Feedback Mechanisms

The detection-correction or feedback systems that the body uses to maintain homeostasis are constantly detecting internal and external conditions. These homeostatic mechanisms then evaluate the conditions to determine whether or not they represent any deviations from the norm. If conditions are outside of the optimal functioning range, the mechanisms take corrective action to bring the body back into balance. In this section, you will explore feedback mechanisms that regulate the internal environment.

Negative Feedback Mechanisms

Feedback is important for any system whose behaviour is a reaction to its environment. The primary mechanism of homeostasis is **negative feedback**, in which a stimulus resulting from a change in the external or internal environment triggers a response that compensates for the change. Homeostatic mechanisms include three elements: a sensor, an integrator, and an effector (**Figure 1**). The **sensor** consists of tissues or organs that detect any change—or stimulus—in external or internal factors, such as the pH, temperature, or concentration of molecules (for example, hormone or glucose molecules).

negative feedback the response of a system that acts to maintain equilibrium by compensating for any changes made to the system

sensor the element of a feedback system that detects changes in the environment

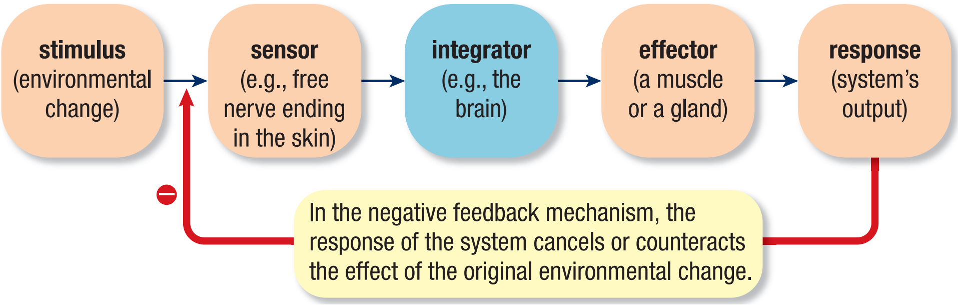

stimulus
(environmental change)
sensor
(e.g., free nerve ending in the skin)
integrator
(e.g., the brain)
effector
(a muscle or a gland)
response
(system's output)
In the negative feedback mechanism, the response of the system cancels or counteracts the effect of the original environmental change.

Figure 1 The components and process of a negative feedback loop that maintains homeostasis

Once the sensor gathers the information, it is transmitted to the **integrator**, which acts as a processing or control centre. The integrator compares the environmental conditions with the optimal functioning conditions, called **set points**. The set point represents a range of values within which a condition controlled by the mechanism is to be maintained. If the environmental condition is outside the set point, the integrator activates the **effector**, which is the system that returns the measured condition to the desired set point. This action is called the response. The sensor and integrator are usually part of the nervous or endocrine system, whereas the effector may include parts of any tissues and organs. To bring internal conditions back into balance, negative feedback mechanisms use antagonistic effectors. The "antagonistic" in their name means that they act to produce the opposite effect of the change recorded by the sensor.

integrator the element of a feedback system that compares existing conditions with ideal conditions

set point the optimal value for a given variable of a system

effector the element (or elements) of a feedback system that acts to return the system to its optimal state

The Thermostat as a Negative Feedback Mechanism

You are probably familiar with the thermostat that maintains a constant temperature in a modern home. Most systems engineered by humans use antagonistic effectors. Heating and cooling systems are good examples. A sensor inside the thermostat measures the temperature (**Figure 2**). A circuit (integrator) in the thermostat compares the measured temperature to the set point programmed by the user. If the temperature increases or decreases by any amount, the integrator circuit activates an electrical effector (either a furnace or an air conditioner), which returns the temperature to the set point. When the temperature falls, the furnace is activated and warmer air is added to the home until the temperature rises to the set point. When the temperature rises, the air conditioner is activated and colder air is added to the room until the temperature falls to the set point. You may find it helpful to keep this example in mind when considering how organ systems act as effectors to maintain homeostasis in the body.

Figure 2 The sensor that measures the temperature in a digital thermostat is a thermistor. A thermistor is a resistor in which electrical resistance varies with changes in temperature.

Negative Feedback Mechanisms in Animals

Mammals and birds also have a homeostatic mechanism that maintains body temperature within a relatively narrow range around a set point. The integrator in this mechanism is located in a brain centre called the hypothalamus. Portions of the hypothalamus act like a thermostat for the body. In the human body, groups of neurons in the preoptic region of the anterior hypothalamus receive information from thermoreceptors in various locations, including the skin, the spinal cord, and the hypothalamus itself. This information is then compared to the set point. For humans, the set point for body temperature has a small range, 35 to 37.8 °C, which is centred on 37 °C. If the temperature deviates from the set point, the hypothalamus activates a set of physiological and behavioural responses to re-establish the normal body temperature.

The particular set of effectors that is activated depends on whether our body temperature is above or below the set point (**Figure 3**). If the temperature drops below the set point, the hypothalamus activates effectors that induce vasoconstriction in the skin. As blood flow through the skin is reduced, less thermal energy is lost to the environment, which causes our body temperature to increase. Additional effectors may induce homeostatic behaviour, such as shivering, which generates body heat. Signals from the hypothalamus make us aware of our lowered body temperature, which may cause us to put on warmer clothes or move to a warmer place.

Investigation **9.2.1**

Investigating Homeostatic Feedback Mechanisms (p. 455)

In this investigation, you will explore how homeostasis is maintained by negative feedback mechanisms.

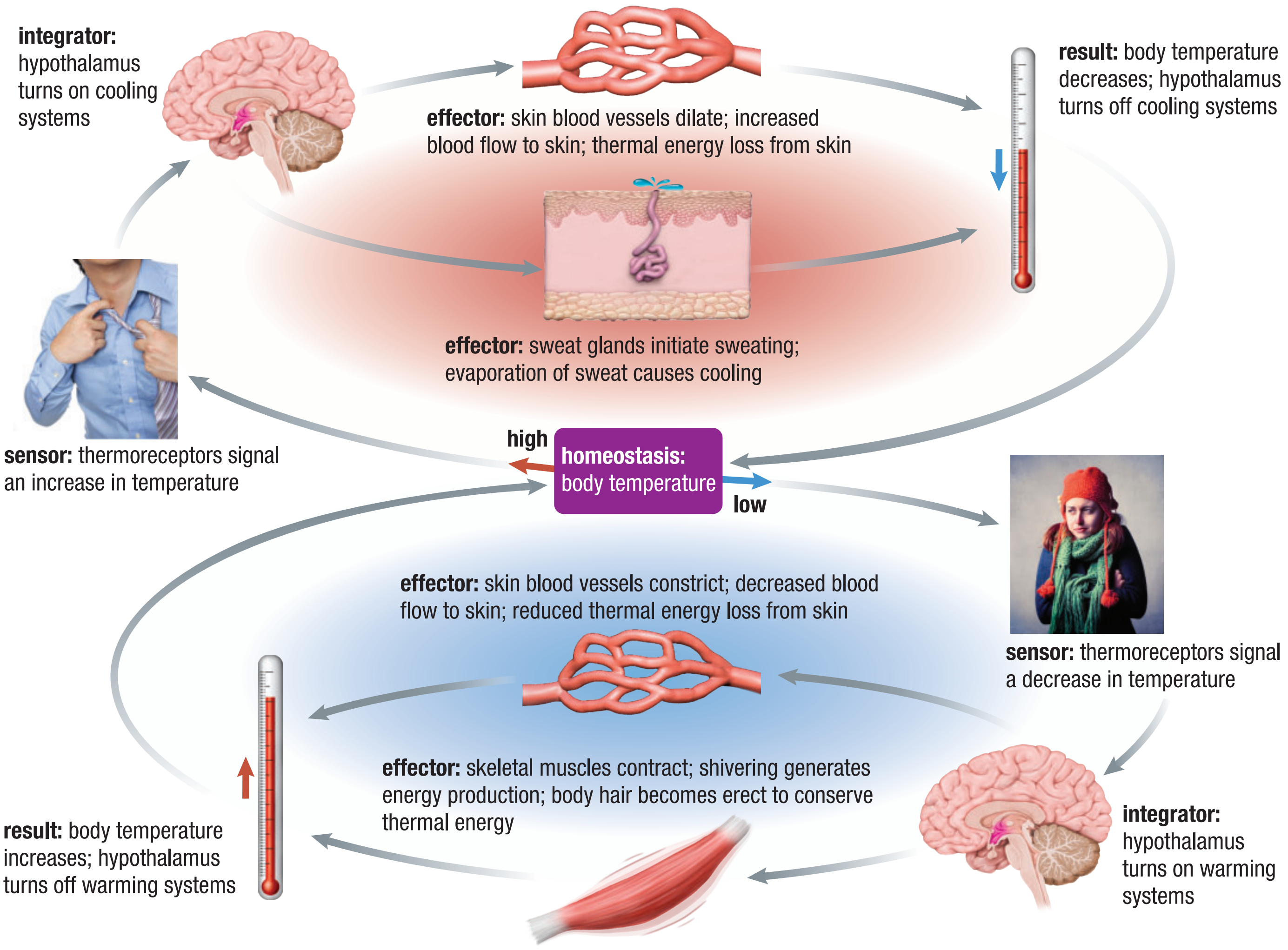

integrator: hypothalamus turns on cooling systems
effector: skin blood vessels dilate; increased blood flow to skin; thermal energy loss from skin
result: body temperature decreases; hypothalamus turns off cooling systems
effector: sweat glands initiate sweating; evaporation of sweat causes cooling
sensor: thermoreceptors signal an increase in temperature
high
homeostasis: body temperature
low
sensor: thermoreceptors signal a decrease in temperature
effector: skin blood vessels constrict; decreased blood flow to skin; reduced thermal energy loss from skin
effector: skeletal muscles contract; shivering generates energy production; body hair becomes erect to conserve thermal energy
integrator: hypothalamus turns on warming systems
result: body temperature increases; hypothalamus turns off warming systems

Figure 3 The evaporation of sweat and dilation of blood vessels provide a negative feedback response by cooling the body. The constriction of blood vessels, shivering, and the erection of body hairs provide a negative feedback response that helps conserve thermal energy.

Figure 4 Homeostatic mechanisms maintain the body temperature of a dog when the environmental temperature is high.

Figure 5 A painted lady butterfly is basking in the sunlight before it takes off.

Another mechanism is activated if our body temperature rises above the set point. The hypothalamus triggers effectors that induce vasodilation in the skin, which increases blood flow and loss of thermal energy to the environment. Signals from the hypothalamus make us aware of overheating, and we may take off warm clothing or move to a cooler area. Other effectors cause the body to sweat, which causes loss of thermal energy when the sweat evaporates.

There are times when the ideal temperature set point changes and the feedback mechanisms work to readjust body temperature to the new set point. For example, if you have an infection caused by a virus or bacteria, the homeostatic effectors increase your temperature, causing a fever. This increase helps the body fight off the infection. Once the infection is cleared, the set point is readjusted to its normal level.

All mammals use similar homeostatic mechanisms to maintain their body temperature set point. Birds and dogs pant to release thermal energy from their body (**Figure 4**). Many terrestrial vertebrates use water to cool off. Mammals and birds are able to regulate their internal temperature within a narrow range, but other vertebrates can thrive within a much broader range. For example, reptiles alter their behaviour in response to changes in body temperature. They absorb thermal energy by basking on sunny rocks during cooler parts of the day, and then move to cooler areas when the temperature becomes warmer. Some large fish, such as tuna and hunting sharks, are able to generate enough thermal energy by contraction of the swimming muscles to maintain a body temperature many degrees above the surrounding water. Even insects use feedback mechanisms to maintain their body temperature. Flight muscles operate best at higher temperatures, so some insects bask in the sunlight to warm their muscles before taking off (**Figure 5**). Other insects, such as dragonflies, bees, and moths, contract their flight muscles in a process similar to shivering in mammals. During the cold winter months, hives of honeybees form large masses to maintain body temperature, and contract their flight muscles to generate thermal energy. Even plants have thermal energy control mechanisms, often to aid in their development and to attract pollinators. For example, the lotus plant minimizes transpiration to stay cool and breaks down carbohydrates to increase thermal energy.

Positive Feedback Systems

positive feedback the response of a system that acts to increase the effect of any changes made to the system

Another type of feedback mechanism is **positive feedback**, which actually increases the change in the environmental condition. Positive feedback mechanisms usually (with some exceptions) do not result in homeostasis, since they cause the system to become unstable. They almost always operate when a continuous increase in some internal variable is required. For example, when an animal is attacked, the body releases adrenaline and hormones into the blood to prime the muscles and organ systems for the "fight or flight" reactions. The release of these chemicals stimulates *further* release, in a positive feedback cycle, making the animal even more fit to survive the attack.

More examples of positive feedback occur during reproduction and child care. The initial uterine contractions during childbirth stimulate the release of the hormone oxytocin from the pituitary gland. Oxytocin increases and intensifies the contractions, which results in the release of more oxytocin and stronger contractions. In this positive feedback cycle, continued contractions, and thus increased pressure, eventually lead to the delivery of the baby as quickly as possible (thus minimizing the risk of harm to both the baby and the mother). Once the baby is delivered, the contractions stop, which, in turn, stops the release of oxytocin. During child rearing, mammalian young suckle milk from the mother. The sensation of suckling stimulates glands in the mother to produce milk. Of course, this milk production leads to more suckling from the young, again causing further milk production in a positive feedback cycle. When the baby is satiated, and ceases to suckle, the milk production is triggered to stop.

Positive feedback mechanisms often operate within a larger negative feedback mechanism, which ultimately works over the long term to bring the body back into balance. Since this chapter deals with maintaining a homeostatic balance, you will be focusing on negative feedback mechanisms.

UNIT TASK **BOOKMARK**

As you work on your Unit Task (page 566), you may want to consider what role positive and/or negative feedback mechanisms play in how your selected factor influences homeostasis.

9.2 Review

Summary

- Negative feedback occurs when a system responds to change by attempting to compensate for this change.
- Homeostasis is accomplished by negative feedback mechanisms. A negative feedback mechanism includes three components: a sensor, which detects changes in the body's conditions; an integrator, which compares the sensory information to the desired set point; and an effector, which acts to re-establish homeostasis.
- All animals use many negative feedback mechanisms to maintain homeostasis, and responses can be physiological or behavioural.
- Positive feedback mechanisms enhance the effect of a change in the internal or external environment, but usually do not result in homeostasis.

Questions

1. Put the following terms in the correct order as they apply to a negative feedback mechanism: effector, stimulus, sensor, response, integrator. Give an example of each. K/U
2. Identify and explain, in simple terms, a negative feedback system found in everyday life. K/U C A
3. For each of the items below, indicate whether you think the statement describes a homeostatic response. Explain your thinking. K/U
   (a) Marathon runners are sweating profusely at 12 km.
   (b) Children enjoy pop, so they drink more.
   (c) The pupils constrict when a light is pointed into the eyes.
   (d) A child spins around and feels dizzy afterwards.
   (e) A patient is infected with a virus and begins to sweat and feel hot.
4. Homeostasis in animals is usually maintained through negative feedback systems rather than positive feedback systems. Why do you think this is so? T/I
5. Explain, in simple terms, how your body uses positive feedback when it reacts to being frightened. K/U C
6. Create a flow chart, similar to Figure 1 (p. 432), to describe the body's reaction to a bacterial infection. K/U C
7. Compare and contrast negative feedback and positive feedback. Give an example of each. K/U
8. Apply what you learned from the thermostat analogy to the way that dragonflies and other flying insects prepare to take off. Be sure to identify the sensor, the integrator, the effector, and the responses. A
9. Plants often require an abundant amount of light to survive. Describe a mechanism that plants use to meet their need for sunlight. K/U
10. When people and other animals become scared or intimidated, their hair often stands on end. Explain why this may happen and how it relates to positive feedback. C A
11. Draw and label a diagram of the negative feedback system for a household thermostat and furnace. Include the following in your diagram: thermostat, furnace, temperature set point, increase and/or decrease arrows. K/U C
12. In addition to negative and positive feedback systems, the body also uses a feed-forward system of control. In a feed-forward system, a mechanism in a system monitors performance inputs rather than outputs, and reacts to maintain a specified state. Using the Internet or other resources, research an example of a feed-forward system that our bodies use for homeostasis. Describe the system in your own words. T/I C A
13. Do you think the clotting of blood after an injury is a positive or a negative feedback response? Explain your reasoning. K/U T/I
14. How might positive feedback control be harmful to the body's systems? Give an example to support your answer. K/U T/I
15. Create a word web or other type of graphic organizer to illustrate possible relationships between the following terms: homeostasis, internal environment, homeostatic mechanism, sensor, integrator, set point, effector, negative feedback. Cluster groups of related terms and connect them, explaining their relationship to one another. Share your graphic organizer with a classmate. K/U T/I C A

WEB LINK

9.3 Thermoregulation

The chemical reactions that give rise to life require a narrow range of temperatures. The habitats that harbour life, however, experience drastic changes in temperature, and organisms must cope with these changes to survive. From deserts in Australia, Africa, and the United States (where the temperature can rise to over 50 °C) to the Arctic tundra (where the temperature can drop to –40 °C), organisms survive and even thrive by using unique systems of internal temperature regulation. If an organism fails to regulate its temperature, however, it can succumb to the extreme temperatures that cause proteins to unfold and lose their functional form or freeze intracellular fluid and cell organelles. In this section, you will learn about the mechanisms, structures, and behavioural adaptations that enable animals to regulate their internal temperature.

Temperature Regulation: A Built-in Thermostat

thermoregulation the regulation of internal temperature by negative feedback mechanisms

As you learned in Section 9.2, temperature regulation, or **thermoregulation**, is a process that is based on negative feedback mechanisms. Temperature receptors, called thermoreceptors, detect any deviations in the external and internal temperatures from an internal set point and then trigger behavioural and physiological responses that act to maintain the internal temperature at the set point. These responses include adjustments in the rate of exothermic reactions within the body (such as metabolism) and adjustments in the rate of thermal energy exchange through the surface of the body. Individual species have adapted to their unique environments through many different methods of thermoregulation, but the mechanisms of thermal energy exchange are universal.

Mechanisms of Thermal Energy Exchange

Regardless of the organism, almost all thermal energy exchange occurs at the surface where the body comes in contact with the external environment. Like any physical body, animals absorb thermal energy if they are cooler than their environment, and release thermal energy if they are warmer than their environment. This exchange occurs through one of four mechanisms: conduction, convection, radiation, and evaporation.

Conduction is the flow of thermal energy between molecules that are in direct contact. Animals lose thermal energy when they come in contact with a colder body. They gain thermal energy when they come in contact with a warmer body. Convection is the transfer of thermal energy within a fluid (liquid or gas). Radiation is the transfer of thermal energy in the form of electromagnetic radiation. All objects, regardless of temperature, radiate thermal energy, and this radiation increases with the temperature of the object. Animals are constantly losing thermal energy to the environment through radiation. However, they also gain thermal energy through radiation, usually by absorbing it from the Sun. The transfer of thermal energy can be aided by evaporation. The most familiar example of this is sweat. Water on the surface of the skin evaporates, absorbing thermal energy from the skin and causing it to cool.

All animals exchange thermal energy with their environment through these four mechanisms, which usually act simultaneously. **Figure 1** illustrates the interaction of these mechanisms in a runner. Assuming that the air in contact with the runner's skin is cooler than the runner's body temperature, the air gains thermal energy by conduction. This is aided by convection and evaporation. As warm air next to the runner's skin surface rises and is replaced by cooler air, convection increases the rate at which thermal energy is lost through conduction. Similarly, as the runner sweats, evaporation occurs and aids in the conduction of thermal energy. The runner's body is also losing energy through outward infrared radiation. At the same time, the runner is gaining thermal energy from solar radiation. A smaller amount is gained by conduction between the runner's feet and the ground. As well, a large amount of thermal energy is generated from the biochemical reactions in the runner's body, which are fuelling the runner. To maintain a stable body temperature, the amount of thermal energy leaving the body must equal the total of the amount produced within the body and the amount absorbed from the environment.

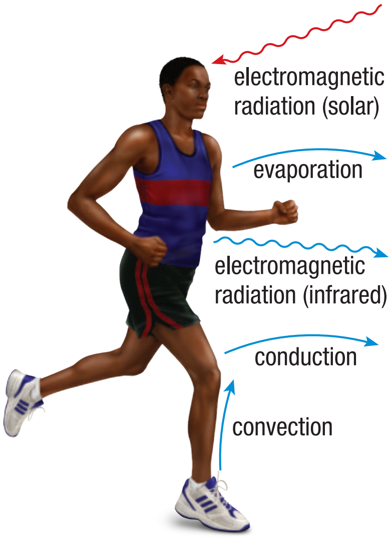

electromagnetic radiation (solar)
evaporation
electromagnetic radiation (infrared)
conduction
convection

Figure 1 The flow of thermal energy into (red) and out of (blue) a runner on a warm, sunny day when the air temperature is 32 °C.

Homeotherms and Poikilotherms, Ectotherms and Endotherms

All animals can be categorized into two groups based on the stability of their body temperature. Animals that maintain a stable internal temperature, regardless of external conditions, are referred to as **homeotherms**. Birds and mammals are homeotherms because they can maintain a body temperature that is often above the ambient environmental temperature. Animals with a body temperature that varies considerably in response to external conditions are referred to as **poikilotherms**. Fish, amphibians, reptiles, and most invertebrates are poikilotherms because their body temperature varies with, and sometimes matches, the temperature of their external environment. Although the body temperature of poikilotherms can vary considerably, these organisms have some degree of control over their body temperature.

homeotherm an animal that maintains a stable body temperature regardless of the temperature of the external environment

poikilotherm an animal whose body temperature varies with, and often matches, the temperature of the external environment

Homeotherms and poikilotherms have different strategies aimed at regulating their body temperature, and they have different responses to changes in external temperature. There are two general types of mechanisms that animals use to regulate their body temperature. Internal physiological mechanisms that generate thermal energy to regulate body temperature are referred to as endothermy. Animals that use these mechanisms are called **endotherms**. Behavioural mechanisms that involve using external sources of energy are considered ectothermy. Animals that use these mechanisms are called **ectotherms**. They regulate their body temperature by absorbing thermal energy from their environment.

endotherm an animal that maintains its body temperature by internal mechanisms

ectotherm an animal that maintains its body temperature by absorbing thermal energy from the environment

Endotherms are more successful than ectotherms at maintaining a stable body temperature, but they are not necessarily more successful animals. The two types of animals have different responses to changes in external temperature. Endotherms can obtain thermal energy from the environment under some conditions, but all ectotherms generate at least some thermal energy from internal reactions. Some ectotherms (for example, those that live in a habitat with a stable temperature) maintain a fairly constant body temperature and are considered homeotherms. Some endotherms allow their body temperature to vary considerably during certain times of day or in different seasons and are considered poikilotherms.

The strategies that are used by ectotherms and endotherms are very different, and each strategy of thermoregulation has its advantages and disadvantages. The difference between endotherms and ectotherms is determined by their metabolic responses to the environmental temperature (**Figure 2**). The metabolic rate of a resting mouse increases steadily as the environmental temperature falls from 25 °C to 10 °C. By contrast, the metabolic rate of a resting lizard typically decreases over the same temperature range. Because of this dependence on thermal energy generated by metabolic processes, endotherms use about 80 % of the energy from their food to maintain their body temperature. Ectotherms, on the other hand, do not use their metabolism to heat or cool themselves, and their energy requirements are much lower than those of endotherms. Ectotherms require much less energy for the same body mass as endotherms.

Endotherms keep their bodies at an optimal temperature by regulating the amount of thermal energy that is generated by internal reactions and the amount of thermal energy that is exchanged with the environment. Endotherms can therefore remain fully active over a wider range of temperatures than ectotherms, but they require a nearly constant supply of energy. Cold weather does not prevent them from foraging, mating, or escaping from predators, but it does increase their energy and food needs. The body temperature of ectotherms tends to fluctuate with the environmental temperature, so ectotherms are usually less active in cold weather. When the environmental temperature drops too low, they become inactive. They move slowly and are unable to capture food or escape from predators. However, their food needs are lower under these circumstances because their metabolic rates are reduced, so they do not have to look actively for food and expose themselves to predators.

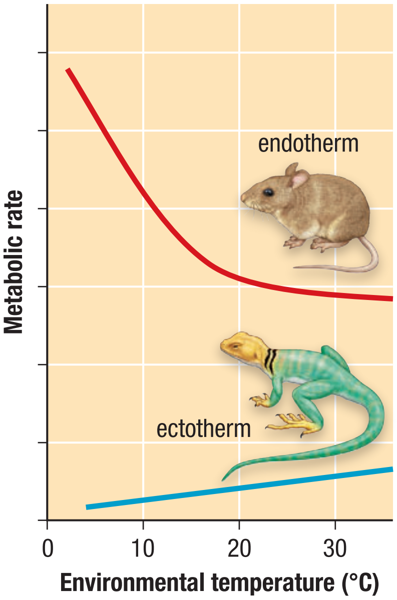


Figure 2 The metabolic rate of an endotherm rises at low environmental temperatures, generating more thermal energy in the body. The metabolic rate of an ectotherm falls at low environmental temperatures, conserving energy.

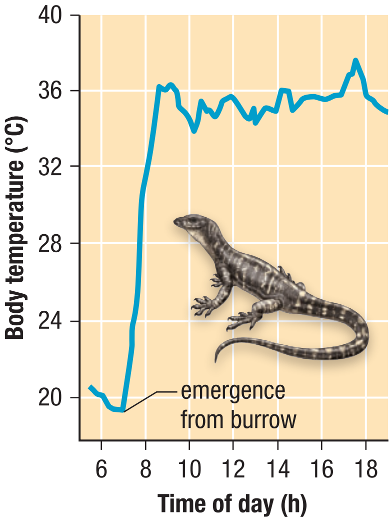


Figure 3 This graph shows the rapid change in a lizard's body temperature when it moves from its cool burrow into the sunlight.

Ectotherms

Ectotherms include many diverse groups of animals, with different abilities to maintain a stable internal temperature. Invertebrates, fish, amphibians, and reptiles are ectotherms, and each has its own method of thermoregulation. Aquatic invertebrates have poor thermoregulation abilities, and their body temperature rarely varies from the external temperature of the water. They live in, or seek, warm or temperate environments where the temperature allows them to have optimal physiological performance. Most fish also have a body temperature that is similar to their surroundings, but they are able to use behavioural adaptations to regulate their internal temperature. For example, the thermal layers of deeper lakes and ponds provide thermoregulatory opportunities for freshwater fish. They remain in deep, cooler water during hot summer days, and they move to shallower areas to feed during early morning and late evening when the air and water temperatures are lower.

Amphibians and lizards rely heavily on conduction and radiation to regulate their body temperature. The most common thermoregulatory behaviour for many lizards is moving between sunny and shady areas. The classic example is a lizard sunning itself on a hot rock. This makes use of both mechanisms of thermal energy transfer and allows the lizard to reach its temperature set point quickly (**Figure 3**). If the lizard becomes too hot, it will retreat to a cooler area to lower its temperature. This continuous and frequent raising and lowering of body temperature allows lizards and some amphibians to keep an almost constant temperature comparable to endotherms.

In addition to thermoregulatory behaviours, some lizards use physiological responses similar to those of endotherms. For example, Galapagos marine iguanas can increase the blood flow to areas of the skin exposed to infrared radiation. The blood warms quickly, and thermal energy is carried to the organs in the core of the body. When the skin is cooled, the blood flow to the skin is restricted, thereby preventing the loss of thermal energy to the external environment.

thermal acclimatization the process by which an animal gradually adjusts to temperature changes in its environment

Many ectotherms undergo seasonal physiological changes. This adaptation, called **thermal acclimatization**, allows them to adjust gradually to changes in external temperature and usually accounts for seasonal variations. For example, in the summer, the bullhead catfish (*Ameiurus* species) can survive in water temperatures as high as 36 °C but not below 8 °C. In the winter, however, the bullhead cannot survive water temperatures above 28 °C but can tolerate temperatures near 0 °C. In some cases, the mechanisms involved can be rather unusual. The wood frog (*Rana sylvatica*), for example, lives in temperate forests where winter temperatures typically drop below freezing. It spends the winter in a frozen state, with no heartbeat, breathing, or brain activity. This state is facilitated by the release of glucose from glycogen stores in the liver and a suspension of the function of insulin, resulting in an accumulation of glucose in the frog's cells. The extremely high concentration of glucose within the cells lowers the freezing point of water. This creates a "slurry" of ice crystals and sugar that prevents the cells from being damaged. When the ice melts, the wood frog thaws and shows little sign of cellular damage.

Endotherms

As you learned in Unit 2, the mitochondria in the cells produce the energy for all of the biochemical processes. However, all of the energy that is available in the glucose molecules does not go into the production of ATP. Some of it is converted into thermal energy. Scientists have estimated that up to 25 % of the basal metabolic rate of most endotherms can be attributed to the energy that is consumed to offset this loss of thermal energy. The body cells of endotherms contain far more mitochondria, and they are proportionately larger than the body cells of ectotherms.

Birds and mammals make up the majority of endotherms, and they have the most elaborate thermoregulatory mechanisms of all animals. Their temperature set points lie within a narrow range: 39 to 42 °C for birds and 36 to 39 °C for mammals. A given species may experience seasonal environmental variations of 70 °C or more, depending on its habitat, but can survive these variations and thrive in almost any environment.

Thermoreceptors on the skin and within the body alert the nervous system to any changes in external or internal temperature. If the core temperature drops below the set point, the body responds by constricting the arteries that supply blood to the skin. This reduces the amount of thermal energy that is lost to the environment by radiation. Shivering and "goose bumps" also regulate the internal temperature. Muscle contractions during shivering generate thermal energy, and the raised hairs in the skin trap air, helping to maintain warmth.

If the core temperature rises above the set point, the body relaxes arteries to allow excess thermal energy to exit via the skin. In a small number of mammals, including humans, the skin contains large numbers of sweat glands. These secrete sweat onto the skin, which removes thermal energy as it evaporates. **Figure 4** summarizes the thermoregulatory responses in humans.

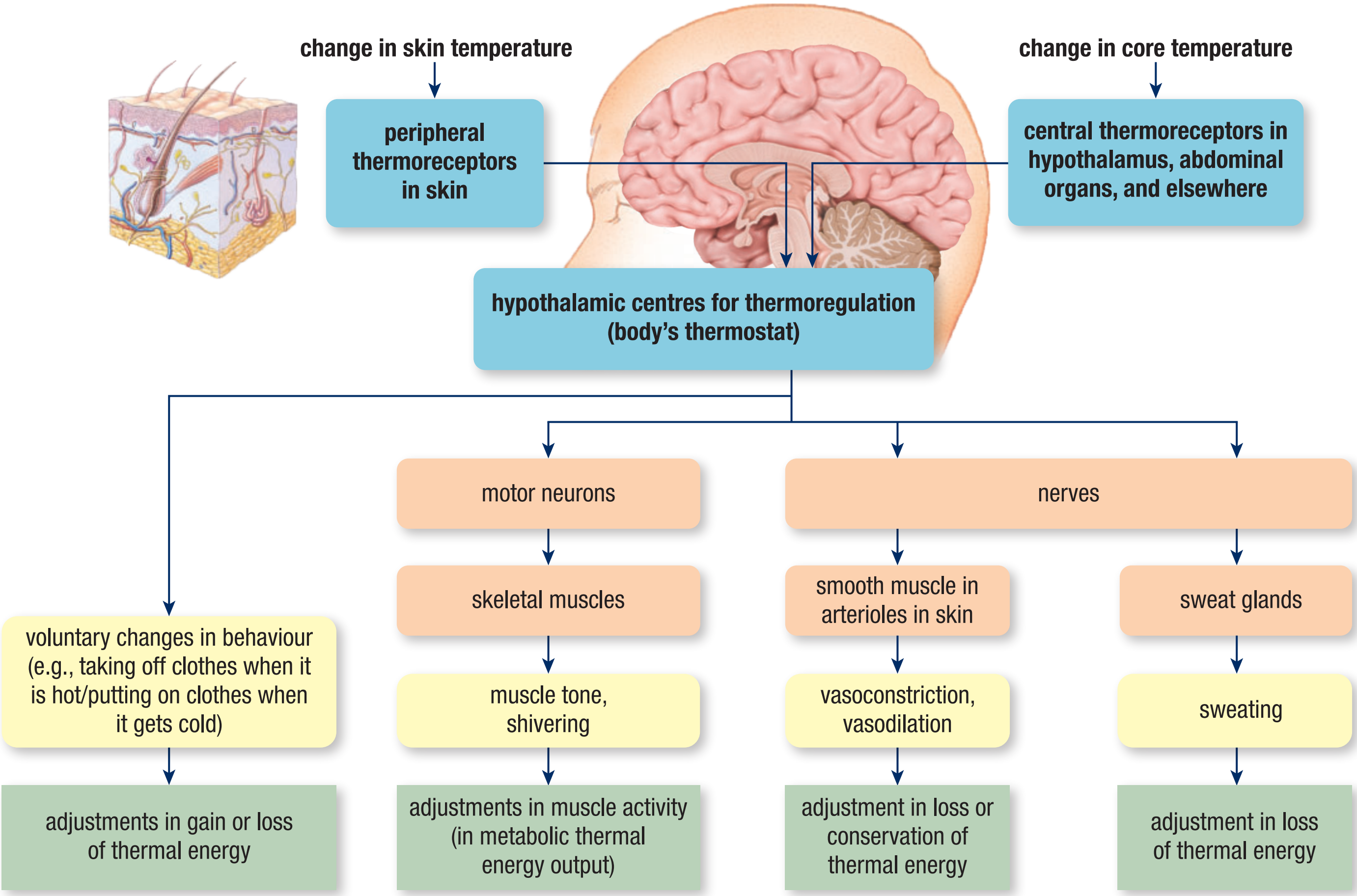

change in skin temperature
peripheral thermoreceptors in skin
change in core temperature
central thermoreceptors in hypothalamus, abdominal organs, and elsewhere
hypothalamic centres for thermoregulation (body's thermostat)
motor neurons
nerves
skeletal muscles
smooth muscle in arterioles in skin
sweat glands
voluntary changes in behaviour (e.g., taking off clothes when it is hot/putting on clothes when it gets cold)
muscle tone, shivering
vasoconstriction, vasodilation
sweating
adjustments in gain or loss of thermal energy
adjustments in muscle activity (in metabolic thermal energy output)
adjustment in loss or conservation of thermal energy
adjustment in loss of thermal energy

Figure 4 Behavioural and physiological responses of mammals to changes in skin and core temperature

TORPOR, HIBERNATION, AND ESTIVATION

Some endotherms have special behavioural and physiological adaptations that help them thrive in even the harshest climates. These endotherms could be considered poikilotherms because their body temperature varies considerably. One of these adaptations is **torpor**, a sleeplike state in which the metabolic rate and body temperature drop in response to variations in daily temperature. An animal may enter into torpor nightly or even daily, as in the case of some bats and other nocturnal animals. The hummingbird uses daily torpor. During the day, the hummingbird is actively feeding, but it cannot feed at night, and so it becomes inactive and allows its body temperature to drop in order to conserve energy. During the night, the hummingbird can use one-fiftieth the energy that it uses during the day and its heart rate can drop from 1260 bpm to 50 bpm. This conserves enough energy for it to survive overnight without feeding.

torpor a short-term state of reduced metabolic rate and body temperature that reduces the demand for energy during the night or day

hibernation a state of greatly reduced metabolic rate and activity that enables an animal to survive the winter by reducing the demand for energy when food is unavailable

estivation a state of torpor that enables an animal to survive the summer by reducing the demand for energy

In cold climates, many endotherms enter a prolonged state of torpor tied to the seasons. This change is usually triggered by a change in the length of the day, which signals the transition between summer and winter. Extended torpor of small mammals during the winter is called **hibernation**, a state of inactivity and significantly decreased metabolic rate. Hedgehogs, groundhogs, and squirrels can experience a 20 °C or greater drop in body temperature during hibernation. The Arctic ground squirrel, for example, hibernates for eight to ten months of the year. It is the only known mammal whose body temperature falls below freezing. During hibernation, its body temperature can dip to as low as –3 °C. At two- to three-week intervals, without rousing from its sleep, the ground squirrel will shiver and shake to bring its body temperature up to a near-normal 36.5 °C. It then stops shivering and its body temperature quickly falls again.

In large mammals, the depth of the torpor is less pronounced and is not considered to be true hibernation by some scientists. The core temperature of a bear drops only a few degrees to around 30 to 32 °C. Although sluggish, bears will frequently awaken—every day almost, and even more often after the young are born—but they do not eat or drink.

Some animals enter seasonal torpor during the summer, when the environmental temperature is high and water is scarce. This is called **estivation**. Animals such as the ground squirrel remain inactive in the cooler temperatures of their burrows during extreme summer heat. Other ectotherms, such as lungfish, many toads and frogs, and some desert-dwelling lizards, survive hot climates by digging into the soil and entering a state of estivation that lasts throughout the hot, dry season.

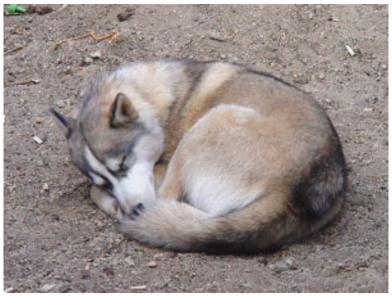


Figure 5 Curling into a ball helps dogs conserve thermal energy.

OTHER THERMOREGULATORY STRUCTURES AND BEHAVIOURS

In addition to the mechanisms already examined, there are many other thermoregulatory behavioural and physiological adaptations used by different species. For example, many insects can use exercise to maintain a core body temperature above the environmental temperature. Such species are known as exercise endotherms. The honey bee can contract antagonistic flight muscles without moving its wings. This method of generating thermal energy is only efficient above 9 to 14 °C. Below this temperature, the bee relies on ectothermic behaviours.

Dogs have an uneven distribution of fur that aids thermoregulation. The fur is thickest over the back and sides of the body and the tail, and thinnest over the belly and the legs. In cold weather, a dog curls up, pulls in its limbs, wraps its tail around its body, and buries its nose in its tail so that only the best-insulated surfaces are exposed to the air (**Figure 5**). Other mammals, such as the muskox and the Arctic fox, adapt to seasonal temperature fluctuations by developing a thick fur coat in the winter and shedding it in the summer.

Certain animals have developed specialized adaptations to lower their body temperature. Some birds fly on a hot day with their legs extended. Dogs and other mammals pant to expel thermal energy from the mouth. Elephants and jackrabbits dissipate thermal energy from the large surface area of their ears (**Figure 6**).

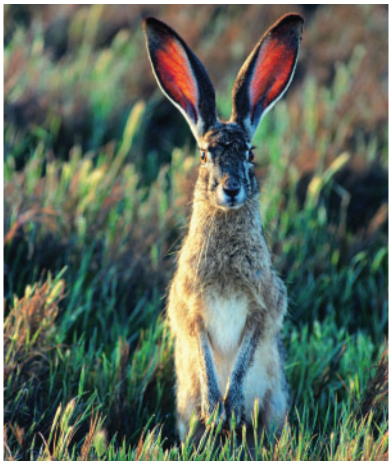


Figure 6 A large surface area of skin with blood vessels close to the surface helps jackrabbits dissipate thermal energy.

Research This

Professor Popsicle

Skills: Researching, Communicating SKILLS HANDBOOK A4.1

Dr. Gordon Giesbrecht of the University of Manitoba investigates the effects of long-term exposure to cold on the human body. Also known as "Professor Popsicle," Dr. Giesbrecht has dropped his body temperature to below 35 °C over 33 times to monitor the effects of hypothermia. Further research shows that children are better able to survive the effects of hypothermia than adults are.

1. Using the Internet and other sources, investigate the work of Dr. Giesbrecht and his research on hypothermia.

A. Describe the different levels of hypothermia, as well as the risks and symptoms of each level. T/I

B. Identify the treatments for each level of hypothermia. T/I

C. Which is more dangerous: hypothermia from air exposure or hypothermia from water exposure? Explain. T/I C

D. Define frostbite, and describe the difference between frostbite and hypothermia. T/I C

E. Summarize your findings in a report. You are free to choose the format for your report. For example, you could choose to do a written report, an oral presentation, or a slide show. C

WEB LINK

9.3 Review

Summary

- Thermal energy is transferred between animals and their environment by conduction, convection, radiation, and evaporation.
- Homeotherms are animals that maintain a fairly constant internal temperature regardless of the external temperature. The internal body temperature of poikilotherms varies in response to the temperature of the external environment.
- Ectotherms are animals that regulate their body temperature by absorbing thermal energy from the environment. Invertebrates, fish, amphibians, and reptiles are ectotherms.
- Endotherms are animals that regulate their body temperature with the internal mechanisms of thermal energy generation, conservation, and dissipation. Endotherms include birds and mammals.
- Both ectotherms and endotherms have behavioural mechanisms that they use to regulate their body temperature.
- Thermal acclimatization is the gradual adjustment to seasonal variations in temperature.

Questions

1. Describe thermoregulation in humans. What occurs when the body temperature is too low? What occurs when it is too high? K/U
2. When an animal wakes in the morning, its core temperature is below the set point. How might an ectotherm and an endotherm respond to this situation differently? T/I
3. Describe the last time that you experienced a notable change in your body temperature. How did your body react? A
4. Using reputable sources, research the use of therapeutic hypothermia for certain medical conditions, such as cardiac arrest, stroke, and brain injury. Briefly summarize your findings. T/I C
5. In the Unit 4 opener, you learned about endurance runner Ray Zahab's expedition across the Sahara Desert. Ray has also run across the frozen Siberian tundra. Describe the physiological dangers of this expedition compared with the Saharan expedition. T/I
6. Extremities such as the hands and feet are usually cooler than 37 °C, which is the body's core temperature. Suggest a reason why they would be cooler. Why would it be important for the body to have a core temperature that is warmer? T/I
7. After learning about thermoregulation habits of ectotherms, suggest a reason why the largest species of ectotherms are found in tropical areas. K/U A
8. Suggest two advantages and one disadvantage of endothermy. K/U T/I
9. In this section, you learned about the wood frog. Using the Internet and other resources, research other frogs that "freeze" during the harsh winter months. Describe their habitat and geography. T/I
10. List several ways, other than torpor, hibernation, and estivation, that animals survive seasons with cold weather. K/U
11. What is the danger of performing heavy physical activity in extremely cold weather? K/U A
12. Compare and contrast estivation and torpor. K/U
13. Bats engage in diurnal torpor (**Figure 7**). Based on what you know about bats and what you have learned about torpor in this section, what do you think diurnal torpor is? Give an example of another organism that engages in diurnal torpor. K/U T/I

Figure 7

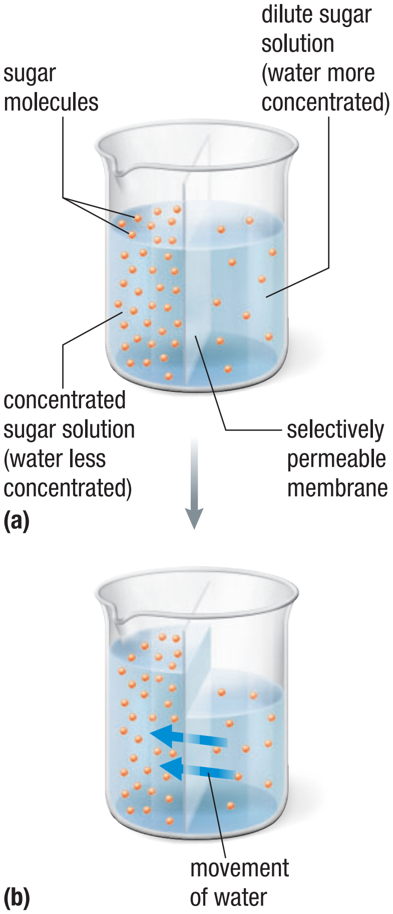
WEB LINK

9.4 Water Balance

The body's internal environment of extracellular fluid must maintain a constant volume, solute content, and often temperature. Humans and many other terrestrial vertebrates require a stable aqueous environment to survive. They carry this aqueous environment inside their body, and they must continuously replenish and maintain it.

Aquatic organisms must also maintain their internal environment, since the conditions of the external environment change in terms of solutes and temperature. The Atlantic salmon (*Salmo salar*) spends part of its life cycle in both freshwater and saltwater environments. For the first two or three years of its life, the salmon lives in freshwater rivers and lakes, where the solute concentration (about 0.1 %) is less than the concentration within its body (about 1.0 %). This concentration gradient results in the uptake of water into the salmon's internal environment, and therefore homeostatic mechanisms must expel the excess water from the body. As the salmon matures, it abandons the freshwater environment for the salt water of the Atlantic Ocean, where the concentration of solutes is about 3.5 %. In this saltwater environment, the salmon experiences a continuous loss of water from its body, which it must replenish.

In addition to changing solute concentrations, there are other important differences between terrestrial and aquatic environments. Because water is not as abundant on land as it is in aquatic environments, terrestrial organisms require mechanisms to conserve water and maintain a homeostatic balance of solutes within their body. In this section, you will consider the following questions: Why do animals need to maintain a water balance? Why do animals need an excretory system?



sugar molecules
dilute sugar solution (water more concentrated)
concentrated sugar solution (water less concentrated)
selectively permeable membrane
(a)
(b)
movement of water

Figure 1 (a) Two solutions have different concentrations. (b) Osmosis occurs when water moves across a selectively permeable membrane from an area of high concentration to an area of low concentration.

Osmosis

In Chapter 2, you learned about the role of osmosis in the homeostatic water balance of cells. During osmosis, water molecules move from a region where they are highly concentrated to a region where their concentration is lower. This movement occurs across a selectively permeable membrane, which allows water but very few solute molecules to flow through. The different water concentrations on the two sides of the membrane are produced by different numbers of solute molecules (**Figure 1(a)**). The side with a lower concentration of solutes has a higher concentration of water molecules. The water moves osmotically across the membrane to the other side, where the water concentration is lower (**Figure 1(b)**). Selective permeability is a key factor in osmosis because it helps to maintain differences in solute concentration on the two sides of biological membranes, such as cell membranes. Proteins are among the most important solutes in establishing the conditions that produce osmosis.

Osmotic pressure is the pressure that results from a difference in water concentration, or a water concentration gradient, between the two sides of a selectively permeable membrane. The greater the water concentration gradient, the greater the osmotic pressure difference between the two sides. A solution with a higher concentration of solute molecules on one side of a selectively permeable membrane is said to be **hyperosmotic** (hypertonic) to a solution with a lower concentration of solutes on the other side. Water tends to move to the hyperosmotic side. The solution with a lower solute concentration is said to be **hypoosmotic** (hypotonic) to the solution with the higher solute concentration. Water tends to move from the hypoosmotic solution. Solutions with the same solute and water concentrations are **isoosmotic** (isotonic).

Water moves across the membrane when the two solutions have different water concentrations. This movement tends to continue until the two solutions are isoosmotic. Water still moves across the membrane even when the solutions are isoosmotic, but the water movement is equal in both directions so there is no net movement.

Another factor that determines whether osmosis will occur is hydrostatic, or water, pressure. If the hydrostatic pressure on one side of a membrane (such as a plant cell membrane) is equal to the osmotic pressure on the other side of the membrane, there is no net flow of water. As water continues to cross the membrane, the internal hydrostatic

osmotic pressure the pressure that results from a difference in solute concentration between the two sides of a selectively permeable membrane

hyperosmotic the property of the solution on one side of a selectively permeable membrane that has the lower concentration of water

hypoosmotic the property of the solution on one side of a selectively permeable membrane that has the higher concentration of water

isoosmotic the property of two solutions that have equal water concentrations pressure begins to build until it balances the external osmotic pressure and osmosis comes to a stop. This occurs despite the fact that the outside of the membrane may have a higher concentration of water molecules. The interplay of osmotic and hydrostatic pressures is important for the structure of plant cells. The water surrounding most plant roots is hypoosmotic relative to the inside of the plant cells. Therefore, water flows into the root cells and then into the cells of stems and leaves. This inflow of water causes the cells to expand and press against the insides of their cell walls, like a balloon blowing up inside a wire-mesh cage. The hydrostatic pressure exerted against the cell walls, known as turgor pressure, gives a plant its rigidity and allows it to stand erect. If the surrounding fluid becomes hyperosmotic in relation to the insides of the cells, or if there is a shortage of water, there will be a drop in turgor pressure and the plant will wilt.

Hydrostatic pressure cannot build in animal cells because they do not have strong cell walls. If an animal cell is surrounded by a very dilute, or hypoosmotic, solution, water molecules will continue to enter the cell until it swells and bursts. If an animal cell is surrounded by a hyperosmotic solution, water molecules will leave the cell by osmosis and the cell will shrink. Both of these situations present serious problems for animals.

Osmoregulation and Excretion

Osmosis is a crucial and ongoing process in the establishment and maintenance of homeostasis. To ensure the chemical and structural stability of the body cells, the internal environment—the extracellular fluid—must be isoosmotic with the intracellular fluid inside of the cells. The process of actively regulating the osmotic pressure of bodily fluids and cells is known as **osmoregulation**. The concentrations of water and solutes, both inside and outside of the cells, must be kept in a constant balance. This requires the continuous movement of water by osmosis and the movement of solutes by diffusion and active processes into and out of the cells.

osmoregulation the process of actively regulating the osmotic pressure of bodily fluids and cells

All organisms need to keep their intracellular and extracellular fluids isoosmotic, but some animals require different levels of active upkeep than others. Many marine animals (such as sponges, jellyfish, sea urchins, squid, and lobsters) do not need to regulate the concentration of their extracellular fluid. The concentrations of their intracellular and extracellular fluids are identical to the concentrations in the external environment (that is, salt water), and water flows in and out of their body freely. In contrast, plants must keep a certain minimum osmotic and hydrostatic pressure within their cells to maintain rigidity and transport nutrients. Many animals (including almost all vertebrates) require more complex control mechanisms to keep the concentrations of intracellular and extracellular fluids constant, but at levels different from the concentrations in the external environment. Some of the most important factors that affect these concentrations are the waste products of metabolism and cell functions, which are continuously eliminated from the body to maintain aqueous homeostasis.

Excretion

To maintain homeostasis, cells regulate their ionic balance and pH balance, in addition to their osmotic concentration. Therefore, certain ions and toxic compounds, such as the metabolites of nitrogenous compounds (for example, amino acids and nucleic acids) must be eliminated. The body's aqueous internal environment acts as a solvent for these wastes, and their elimination helps maintain osmotic pressure and concentration. This is why excretion is so closely tied to the process of osmoregulation. For most terrestrial animals, the maintenance of osmotic concentration while eliminating nitrogenous wastes can be difficult, since it requires significant amounts of water, which may not be readily available depending on the season or geographical location.

Animals maintain their ionic and pH balance through the process of excretion. Excretion is the elimination of waste products and foreign matter from the body.

It serves to maintain the ionic and osmotic equilibrium that is necessary for cell functions. The body system that regulates the removal of wastes is the excretory (or urinary) system, and its main organs are the kidneys and the bladder. As the body processes proteins during metabolism, it produces waste molecules, which the liver converts into soluble metabolites. The kidneys can filter out these metabolites and eliminate them from the body with other aqueous waste, maintaining the water and pH balance of the internal environment.

Waste nitrogen is produced in different forms for different groups of animals (**Figure 2**). Bony fishes produce ammonia, mammals and cartilaginous fishes (sharks, skates, rays) produce urea, and most birds produce uric acid as nitrogenous waste.

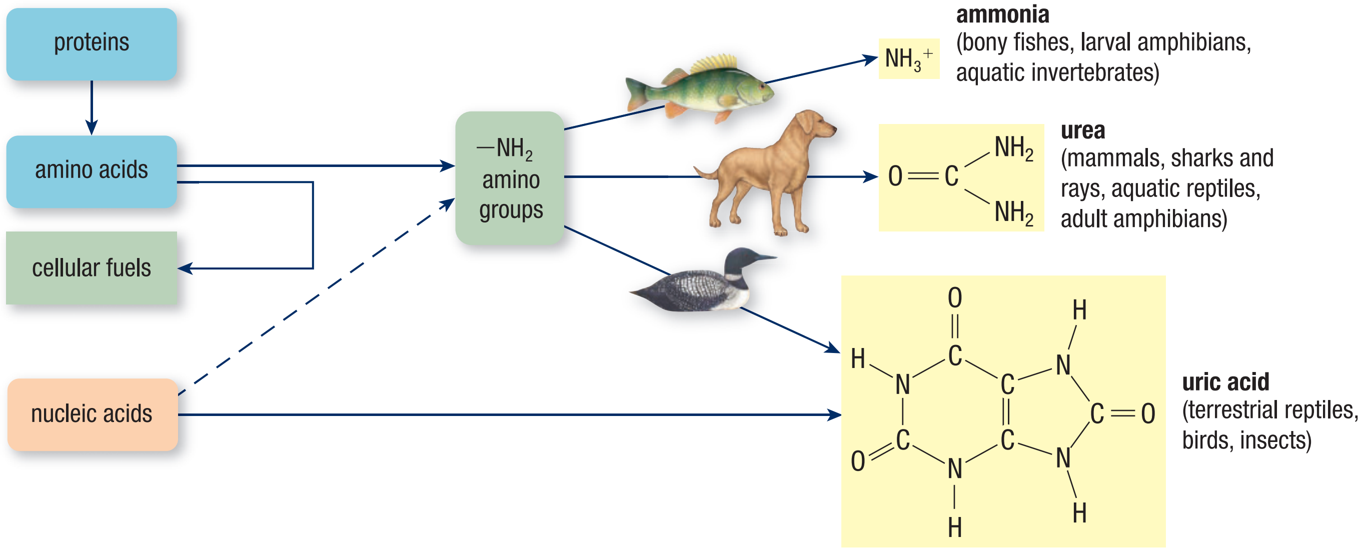

proteins
amino acids
cellular fuels
nucleic acids
$-NH_2$ amino groups
NH_3^+
ammonia
(bony fishes, larval amphibians, aquatic invertebrates)
O=C
NH_2
NH_2
urea
(mammals, sharks and rays, aquatic reptiles, adult amphibians)
uric acid
(terrestrial reptiles, birds, insects)

Figure 2 Nitrogenous wastes excreted by different animal groups

As you learned in Chapter 1, the building blocks of proteins are amino acids. An amino acid contains a nitrogen atom bonded to two hydrogen atoms, called an amino group. In the process of deamination, which occurs in the liver, the amino group is removed from each amino acid that comes from the breakdown of a protein. The amino group is then converted to ammonia. The rest of the amino acid, which is mostly carbon and hydrogen, is oxidized to produce energy.

Ammonia, NH_3, the by-product of deamination, is a highly toxic substance. A buildup of as little as 0.005 mg/L can kill a human. It can be transported and secreted only in very dilute solutions. Animals with an abundant supply of water (such as bony fish and marine invertebrates) are able to secrete ammonia directly from the body in this very dilute form. In mammals, some reptiles, and most amphibians, the liver combines ammonia with HCO_3^- to create urea, a very soluble substance with 0.001 % the toxicity of ammonia. In fact, 33 mg of urea can be dissolved in just 100 mL of blood with no toxic effects. Although the chemical reactions that produce urea require more energy than the reactions that produce ammonia, urea can be eliminated from the body with less water, allowing terrestrial animals to maintain their water balance.

Other animals conserve water even more efficiently. For example, birds and some terrestrial invertebrates produce uric acid as their nitrogenous waste product. Uric acid is not toxic, but its key feature for these smaller animals is its low solubility. As urine is concentrated in its final stages, the uric acid forms crystals that are expelled from the body with a minimal amount of water. (The white substance in bird droppings is uric acid crystals.) Most animals are able to form all three of these nitrogen compounds, but the primary method of excretion depends on a balance among water conservation, toxicity, and energy requirements. You will learn about the excretory system and the functions of its organs in humans in Section 9.5.

UNIT TASK **BOOKMARK**

You may want to consider thermoregulation (Section 9.3) or water balance (Section 9.4) as a factor for your Unit Task on page 566.

9.4 Review

Summary

- All organisms must maintain a balance between their internal aqueous environment and the external environment.
- Osmoregulation ensures that the intracellular and extracellular fluids are isoosmotic, and it keeps the internal concentrations of water and ions different from the concentrations in the external environment.
- Osmoregulation is closely linked to the process of excretion, in which animals expel the waste products of metabolism to the external environment.
- The excretory system removes nitrogenous waste, excess water, and toxic compounds from the body. The main organs in the excretory system are the liver and the kidney.

Questions

1. (a) Describe the similarities and differences between diffusion and osmosis.
   (b) Why is osmosis particularly important for biological functions? K/U
2. Why do cells need to use osmoregulation? K/U
3. What is the relationship between osmoregulation and excretion? K/U
4. Explain the advantages and disadvantages for terrestrial animals of creating urea rather than other forms of nitrogenous waste. K/U
5. Why is it an advantage for birds to create uric acid as their nitrogenous waste compound? (Think in terms of birds' specialized adaptation of flight.) K/U T/I
6. What animals do you think would produce more urea: carnivores with a high-protein diet or herbivores with a high-carbohydrate diet? Which would require more water? Why? K/U T/I
7. Predict what would happen if a cell found in an ocean with a high concentration of salt was suddenly placed in a beaker of fresh water. T/I A
8. Excretion is studied in Grade 8 science. Describe to a Grade 8 student the importance of excretion in relation to osmoregulation. K/U C
9. Describe why a walleye living in Lake Ontario cannot survive in the Bay of Fundy (**Figure 3**). In your description, refer to hypoosmoticity, hyperosmoticity, and isoosmoticity. K/U T/I C

Figure 3 A walleye from Lake Ontario

10. Explain the difference between the terms "hypertonic" and "hyperosmotic." K/U
11. How do mineral salts and other particles such as glucose, urea, and proteins participate in osmotic regulation? K/U T/I
12. Why do you think sugar and salt are used in the drying of fruit and meat? K/U T/I A

9.5 The Excretory System

In multicellular organisms, individual cells cannot effectively secrete wastes to the external environment. One of the main functions of the excretory system (aided by osmoregulation) is to concentrate wastes and expel them from the body. The second main function of the excretory system is to regulate fluids and water within the body. Most metabolic wastes and toxins are dissolved in the body's internal environment, so maintenance of the body fluids is essential for keeping the body free of waste products and enabling it to function properly. In this section, you will learn about the functions of the excretory system and examine how the excretory system works in simpler organisms and in more complex organisms, such as humans and other mammals.

Excretion in Invertebrates and Non-mammalian Vertebrates

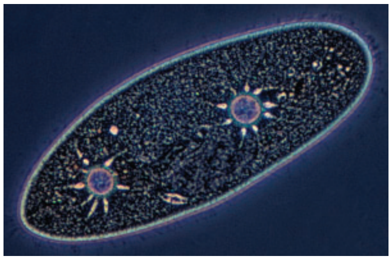


Figure 1 Some single-celled organisms, such as the paramecium, excrete material directly into the external environment via contractile vacuoles.

Single-celled organisms and simple multicellular organisms produce the same metabolic wastes and toxic compounds as more complex organisms. These waste products must be excreted to maintain homeostasis. Simple organisms have an advantage over more complex organisms because their cells are in constant contact with the external environment. Wastes are excreted directly from their cells, and the water currents in the external environment carry the wastes away. A greater challenge for simple organisms is maintaining a fluid balance with the external environment. Free-living single-celled organisms, such as the paramecium, have an internal environment that is hyperosmotic to their surroundings (**Figure 1**). If they were not able to maintain a fluid balance, they would continuously absorb water from the environment and eventually burst. To expel excess water, these protozoans have **contractile vacuoles**, which pump out water to maintain osmotic balance.

contractile vacuole a structure in a single-celled organism that maintains osmotic equilibrium by pumping excess fluid out of the cell

metanephridium an excretory organ in some invertebrates that is used to reabsorb and eliminate wastes

In more complex organisms, the excretory system must take on different forms to meet different challenges. Some invertebrate animals, such as the earthworm, have excretory organs called **metanephridia** (singular: metanephridium) that expel wastes from the body (**Figure 2**). In each segment of the earthworm, hemolymph (a fluid that serves as both interstitial fluid and blood) flows into a pair of metanephridia, which are twisted into convoluted shapes to maximize their surface area. Ions and wastes are reabsorbed from the hemolymph and secreted (along with water) into a saclike organ called a bladder. From there, the excess water and waste products are secreted to the external environment through a pore in the side of the worm's body.

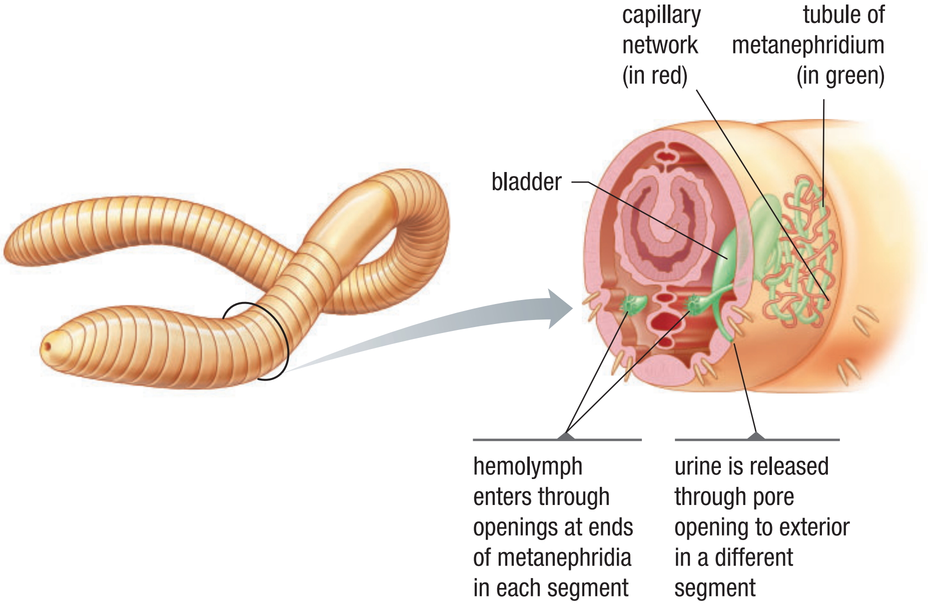

capillary network (in red)
tubule of metanephridium (in green)
bladder
hemolymph enters through openings at ends of metanephridia in each segment
urine is released through pore opening to exterior in a different segment

Figure 2 A metanephridium of an earthworm

Insects such as the grasshopper excrete wastes using a set of organs called **Malpighian tubules**. The closed ends of these organs are immersed in the hemolymph. The open ends empty into the intestines (**Figure 3**). Several substances, such as uric acid (the nitrogenous waste product) and potassium and sodium ions, are secreted into the tubules. As the concentration of these substances increases, water moves osmotically from the hemolymph into the tubule to form a dilute waste solution. The waste solution (urine) then travels to the intestines of the insect, where specialized cells reabsorb most of the K^+ and Na^+ back into the hemolymph. This causes water to move from the intestines back into the hemolymph by osmosis—an important water conservation measure. The uric acid that is left behind forms crystals and is expelled with the insect's digestive waste products.

Malpighian tubule the main organ of excretion in insects, which is used to carry wastes to the intestines

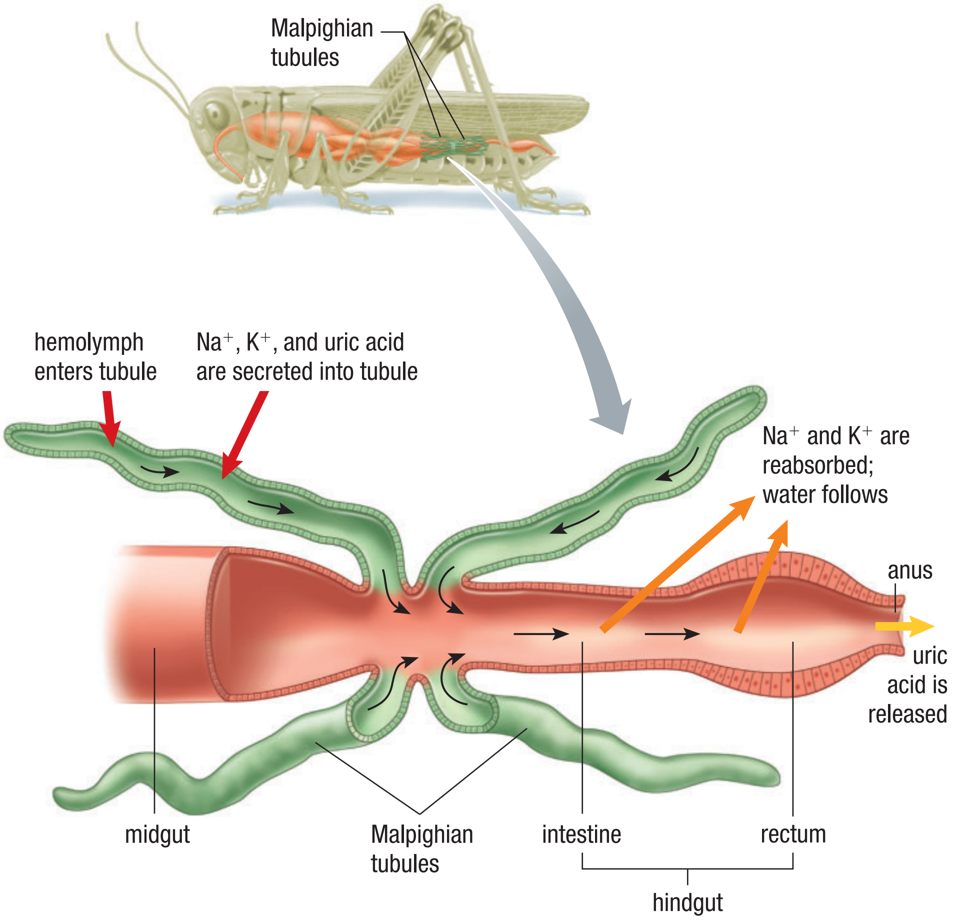


Figure 3 Excretion through Malpighian tubules in a grasshopper

Terrestrial reptiles and most birds conserve water by excreting nitrogenous wastes in the form of an almost water-free paste of uric acid crystals. This is excreted into the cloaca (end of the digestive system) and removed from the body along with the digestive wastes. The white substance in bird droppings is uric acid. The darker substance is feces.

Reptiles and birds that live in or around salt water take in large quantities of salt with their food and rarely or never drink fresh water. These animals usually excrete excess salt through specialized salt glands located in the head (**Figure 4**). The salt glands remove salts from the blood by active transport. The salts are secreted to the environment as a water solution, in which the salts are two to three times more concentrated than in body fluids. The secretion exits through the nostrils of birds and lizards, and as salty tears from the eye sockets of sea turtles and crocodilians.

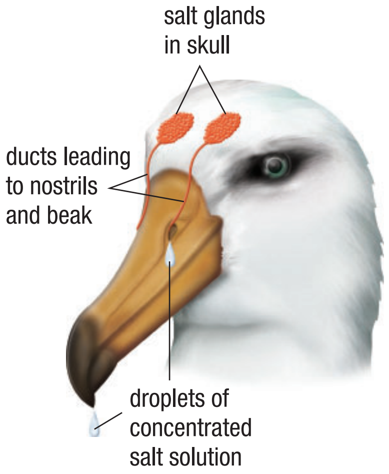

salt glands in skull
ducts leading to nostrils and beak
droplets of concentrated salt solution

Figure 4 Saltwater birds get rid of excess salt through salt glands in the head.

The Human Excretory System

nephron the tiny functional unit of the kidney that filters wastes from the blood

The excretory systems of all vertebrates, including humans, use specialized tubules, called **nephrons**, which regulate the water balance in the body and conduct excretion (**Figure 5**). These tubules are located in the major organs of the excretory system—the kidneys. The kidneys, ureters, bladder, and urethra together make up the human excretory system.

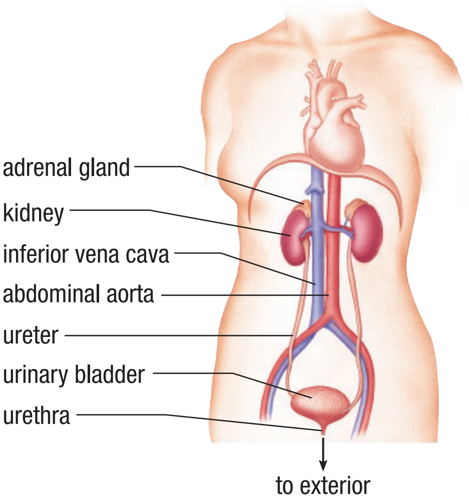


Figure 5 The human excretory system

Kidneys

The kidneys play a critical role in removing wastes, balancing blood pH, and maintaining the body's water balance. Mammals have two kidneys, one on each side of the vertebral column. In humans, the average kidney has a mass of about 150 g and receives about 25 % of the cardiac output (roughly 1.25 L/min). Blood is supplied to the kidney through the renal artery. ("Renal" refers to the kidney.) The kidney filters the wastes from the blood, and the clean blood exits the kidney through the renal veins. **Figure 6** shows the internal structure of a kidney. The outer layer of the kidney is called the renal cortex. An inner layer, called the medulla, is found beneath the cortex. A hollow cavity, called the renal pelvis, connects the kidney to the ureter, through which urine passes to the urinary bladder. Once the bladder is full (with roughly 300 to 400 mL of urine), the urine exits the body through the urethra.

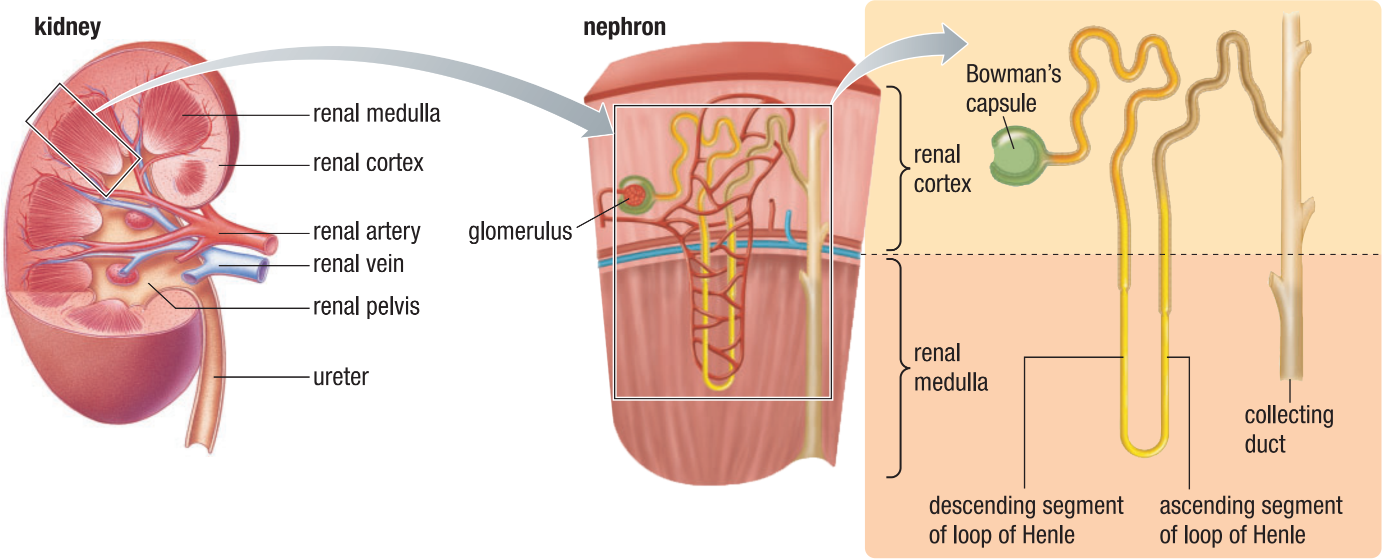


Figure 6 Anatomy of the kidney. Each kidney contains about 1 000 000 nephrons.

NEPHRONS

Each kidney contains about 1 000 000 nephrons, which are the functional unit of the kidney. Nephrons are differentiated into regions, which perform the series of steps that are involved in excretion (**Figure 7**). At one end is the **Bowman's capsule**, a small folded structure that encircles a group of blood capillaries, the **glomerulus**, in the cortex. The glomerulus performs the first steps in the filtration of blood to form urine. Blood is supplied to the glomerulus by the **afferent arteriole** and, after being filtered, exits via the **efferent arteriole** and is carried to a net of capillaries called the **peritubular capillaries**. The peritubular capillaries surround the tubules that carry away the urine and allow for the reabsorption of essential ions and minerals back into the bloodstream.

During the first steps of filtration, components of the unfiltered blood pass from the glomerulus into the Bowman's capsule and enter a **proximal convoluted tubule**, which lies in the renal cortex. This tubule descends into the medulla and forms a U-shaped structure called the **loop of Henle** before rising again to form a **distal convoluted tubule**. The distal tubule drains the urine into a branching system of collecting ducts that lead to the renal pelvis, which then empties through the ureter to the bladder.

CAREER LINK

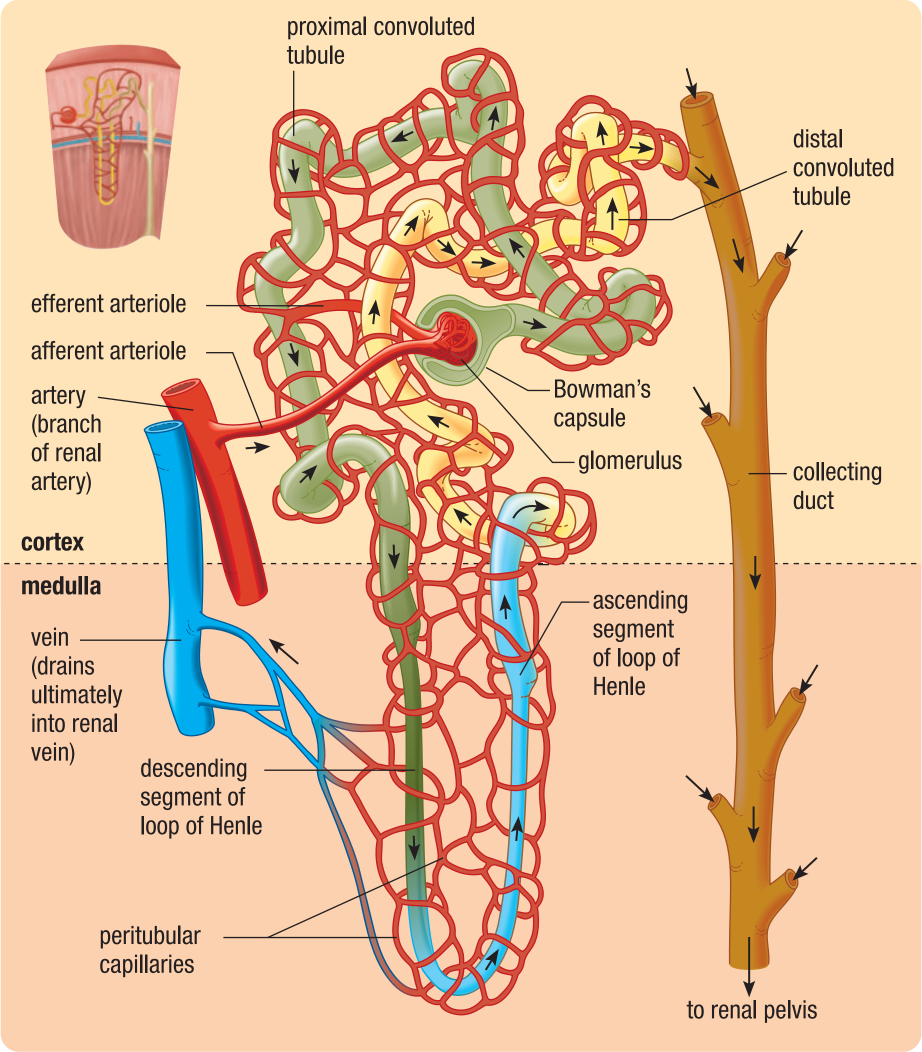

proximal convoluted tubule
distal convoluted tubule
efferent arteriole
afferent arteriole
artery (branch of renal artery)
Bowman's capsule
glomerulus
collecting duct
cortex
medulla
vein (drains ultimately into renal vein)
ascending segment of loop of Henle
descending segment of loop of Henle
peritubular capillaries
to renal pelvis

Figure 7 A nephron and its blood circulation

Bowman's capsule a small folded structure in the human kidney that encircles the glomerulus

glomerulus a network of capillaries within the Bowman's capsule that performs the first step in the filtration of blood

afferent arteriole a vessel that supplies blood to the nephrons in the human kidney

efferent arteriole a vessel that carries away filtered blood from the nephrons in the human kidney

peritubular capillaries a net of capillaries in the nephrons that reabsorb essential ions and minerals from filtered blood

proximal convoluted tubule the duct portion of a nephron that connects the Bowman's capsule to the loop of Henle

loop of Henle the U-shaped part of the duct that connects the proximal convoluted tubule to the distal convoluted tubule

distal convoluted tubule the duct portion of a nephron that connects the loop of Henle to the ducts that lead to the renal pelvis

The Formation of Urine

As alluded to previously, the different sections of the nephron have specialized functions in the formation of urine and the conservation of water. In mammals, urine is hypoosmotic to the surrounding body fluids. This means that water tends to move from urine into the body fluids, an adaptation that conserves water. Three features of the nephrons interact to conserve nutrients and water, balance salts, and concentrate wastes for excretion: the arrangement of the loop of Henle, which descends into the medulla and rises back into the cortex; the differences in permeability of successive parts of the nephrons; and the concentration gradient of molecules and ions in the interstitial fluid of the kidney, which gradually increases from the cortex to the deepest levels of the medulla.

Urine formation is the result of three interrelated processes: filtration, reabsorption, and secretion. Filtration occurs as body fluids move from the blood into the Bowman's capsule. Reabsorption transfers essential solutes and water from the nephron back into the blood. Secretion transfers materials from the blood back into the nephron. In this section, you will examine each of these processes, which occur in different parts of the nephron.

Filtration

The process of urine formation begins at the Bowman's capsule (**Figure 8**). The cells of the Bowman's capsule and the capillaries that it surrounds form a selectively permeable membrane, with spaces just wide enough to admit water, ions, small nutrient molecules (such as glucose and amino acids), and nitrogenous waste molecules (primarily urea). The higher pressure of the blood in the glomerulus drives fluid that contains these molecules and ions into the capsule. Blood cells, platelets, and plasma proteins are too large to pass through and are retained in the capillaries. The fluid that enters the Bowman's capsule, which contains only the smaller molecules (including

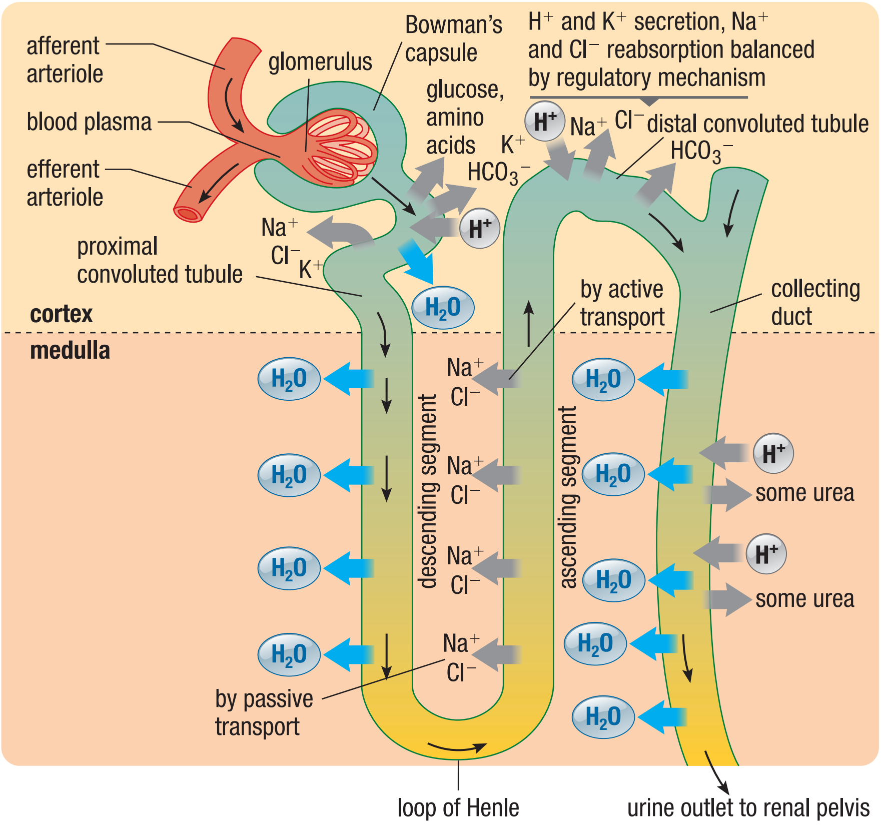


Figure 8 The movement of water, ions, and other molecules through the collecting tubules and nephrons in the kidney

metabolic waste), is an ultrafiltrate of the blood. The process in which fluid and small molecules pass into the Bowman's capsule is known as **filtration** (**Figure 9**).

About 1400 L of blood pass through the kidneys every day, and the Bowman's capsules filter about 180 L of fluid from this blood. The human body contains roughly 2.75 L of blood plasma. This means that the kidneys filter the entire contents of the blood plasma 65 times every day. Only about 1.5 L of the daily filtrate is excreted as urine. The rest consists primarily of water and is reabsorbed into the nephrons.

filtration the process in which blood and fluid pass through a selectively permeable membrane

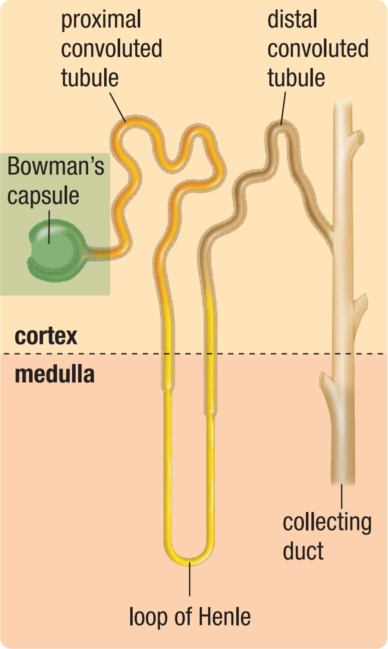


Figure 9 Filtration occurs in the Bowman's capsule.

Reabsorption

The fluid that is filtered into the Bowman's capsule contains urea, water, ions, and other molecules that are in the same concentrations as they are in the blood plasma. The fluid enters the proximal convoluted tubule, where **reabsorption** occurs (**Figure 10**). Water, ions, and nutrients are transferred back into the interstitial fluid via both passive and active methods. Specialized ion pumps transport potassium, K^+; sodium, Na^+; and chlorine, Cl^-, from the filtrate into the fluid surrounding the tubule. Active transport proteins, embedded in the walls of the tubule, reabsorb the amino acids, glucose, and other nutrients out of the filtrate. Urea and other unwanted compounds are not reabsorbed. The inner walls of the tubule are covered with microscopic extensions called microvilli. These extensions greatly increase the total surface area that is available for the reabsorption of solutes. All of the reabsorption processes make the filtrate hypoosmotic to the interstitial fluid, and this causes water to flow out of the tubule and into the interstitial fluid by osmosis. The movement of water is further facilitated by membrane proteins called **aquaporins**, or water channels, which form passages for additional water molecules to flow out of the tubule. The aquaporins ensure that the maximum amount of water is removed from the tubule during the reabsorption process. The proximal convoluted tubule reabsorbs 67 % of the Na^+, K^+ , and Cl^-; 65 % of the water; 50 % of the urea; and nearly all of the amino acids, glucose, and other nutrients. This highly efficient process saves energy and allows the body to maximize the use of these nutrients.

The nutrients and water that are reabsorbed in the proximal convoluted tubule enter the peritubular capillaries. The remaining fluid, which has a high concentration of urea and other wastes that are not reabsorbed, moves through the proximal convoluted tubule into the descending portion of the loop of Henle. There, additional water is reabsorbed by osmosis and the aquaporins. The outward movement of water concentrates the molecules and ions inside the tubule. As the fluid moves into the ascending portion of the loop of Henle, Na^+ and Cl^- are reabsorbed into the interstitial fluid. In the first part of the ascending segment, the concentrations are high enough to move Na^+ and Cl^- out of the tubule by passive diffusion. Toward the top of the ascending segment, these ions are moved out by active transport. Thus, as the fluid flows through the entire loop of Henle, water, nutrients, and ions have been conserved and returned to the body fluids, and urea and other nitrogenous wastes have become concentrated in the filtrate so the total volume of the filtrate in the nephron has been greatly reduced.

As the fluid continues along its path, it enters the distal convoluted tubule, where additional water and salts are removed. More ions and solutes move out of the fluid than into it; this causes the further transport of water out of the tubule by osmosis through the aquaporins. The amounts of urea and other nitrogenous wastes remain the same.

The concentrated urea and other wastes flow into the collecting ducts, which further concentrate the urine. The collecting ducts descend from the cortex of the kidney and through the medulla. They are permeable to water, but not to salt ions. The concentration of solutes increases with depth as the fluid descends into the medulla. This causes further removal of water through the ducts, greatly increasing the concentration of the urine. Near the bottom of the medulla, the walls of the collecting ducts contain passive urea transporters, which allow some of the nitrogenous wastes to pass from the duct into the interstitial fluid. This urea adds significantly to the concentration gradient of solutes in the medulla.

reabsorption the transfer of water, ions, and nutrients back to the interstitial fluid via passive and active transport

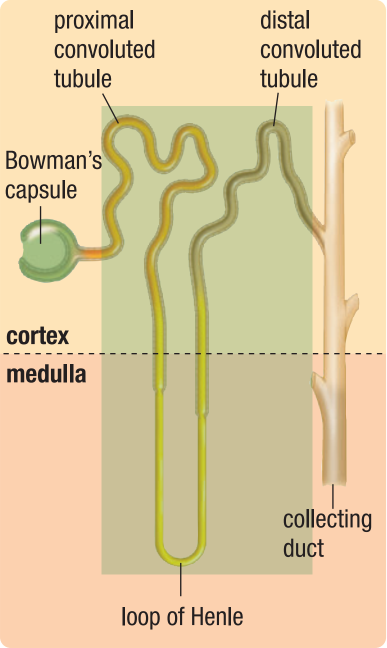


Figure 10 Reabsorption occurs in the proximal convoluted tubule, the loop of Henle, and the distal convoluted tubule.

aquaporin a membrane protein that passively transports water molecules

secretion the removal of waste materials from the blood and intercellular fluid

Secretion

Secretion is the removal of waste products from the blood and interstitial fluid (**Figure 11**). During the process of urine formation, wastes are secreted at several points in the nephron. Some wastes are secreted from the interstitial fluid into the proximal convoluted tubule. H^+ ions are actively secreted, and the products of detoxified poisons (from the liver) are passively secreted. (Many water-soluble drugs, such as penicillin and other medications, and their metabolites are also secreted into the nephron and excreted in the urine.) Small amounts of ammonia are secreted into the tubule. The secretion of H^+ ions into the filtrate helps to balance the acidity that is constantly generated in the body by metabolic reactions. H^+ secretion is coupled with HCO_3^- reabsorption from the filtrate to the plasma in the peritubular capillaries.

In response to hormones triggered by changes in the salt concentrations in the body, varying amounts of K^+ and H^+ are secreted into the filtrate in the distal convoluted tubule. Additional active secretion of H^+ occurs in the collecting ducts. The balance of ions established in the blood, urine, and interstitial fluid is essential for regulating the pH level of the blood and body fluids. In this way, the kidney acts as a "safety valve." If the acidity of the body fluid rises beyond the levels that can be controlled by the blood's buffer system, the excess H^+ ions are secreted into the collecting ducts and excreted in the urine.

When urine reaches the bottom of the collecting ducts, it is roughly four times as concentrated with waste molecules as the extracellular fluid. From the collecting ducts, urine flows into the renal pelvis, through the ureters, and into the urinary bladder. From the bladder, the urine exits through the urethra into the external environment.

Table 1 provides a summary of the functions of the different parts of the kidney as wastes are removed from the blood and urine is produced.

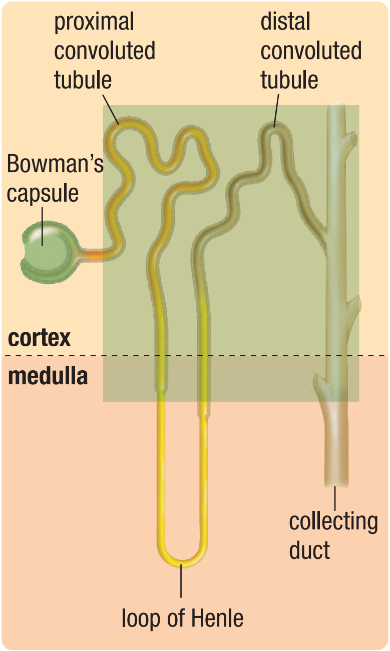


Figure 11 Secretion occurs in the proximal and distal convoluted tubules, and the collecting duct.

Table 1 Functions and Roles of Different Parts of the Nephron and Collecting Ducts

Segment	Location	Primary function	Comparison to interstitial fluid	Result of passage
glomerulus and Bowman's capsule	cortex	Ions (Na^+, Cl^-, and H^+), small nutrients (glucose), nitrogenous wastes (amino acids, urea, and uric acid), vitamins, and minerals are filtered into the Bowman's capsule.	isoosmotic	Water and small substances, but no proteins, pass into the nephrons.
proximal convoluted tubule	cortex	Ions are actively reabsorbed, water leaves through the aquaporins, and H^+ ions are actively secreted. Glucose, amino acids, and other nutrients are actively absorbed.	isoosmotic	Some of the ions, water, and urea, and all of the nutrients return to the interstitial fluid. The pH balance is maintained.
descending portion of loop of Henle	cortex into medulla	Water leaves through the aquaporins.	isoosmotic at top to hyperosmotic at bottom	Additional water is returned to the interstitial fluid.
ascending portion of loop of Henle	medulla into cortex	Na^+ and Cl^- are actively transported out. There is no entry of water and no movement of urea.	hyperosmotic at bottom to isoosmotic at top	Additional ions are returned to the interstitial fluid.
distal convoluted tubule	cortex	K^+ and Na^+ are secreted via active transport into the urine. Na^+ and Cl^- are reabsorbed. Water moves into the urine through the aquaporins.	hypoosmotic at beginning to isoosmotic at junction with collecting ducts	The ionic and pH balance are maintained.
collecting ducts	cortex through medulla, into renal pelvis	Water moves out via the aquaporins. There is no movement of ions. Some urea leaves at the bottom of the collecting ducts.	isoosmotic at junction to hyperosmotic at junction with renal pelvis	More water and some urea are returned to the interstitial fluid. Some H^+ ions are added to the urine.

Mini Investigation

Treating Lead Poisoning

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK A1, A2.1

The standard treatment for lead poisoning is the ingestion of a chelating agent. The chelating agent binds with the lead and allows it to dissolve and be secreted with the urine. In this investigation, you will model the process that enables lead to be removed from the body through the kidneys. You will use sodium bicarbonate solution to simulate the blood, and calcium to simulate the actions of the lead in the body. The calcium ions will bind with carbonate ions in the simulated blood just as lead ions settle into red blood cells and interfere with the production of hemoglobin, the oxygen-carrying compound. The calcium in the calcium chloride will act like lead in the body and bind with the carbonate. EDTA is the chelating agent.

Equipment and Materials: safety goggles; 2 medicine droppers; 3 beakers (50 mL); 3 labels: lead (calcium chloride), blood (sodium bicarbonate solution), chelating agent (EDTA); 3 spatulas or plastic knives; balance; 100 mL graduated cylinder; 3 stirring rods; 0.6 g sodium bicarbonate; 0.6 g calcium chloride ✋; water; 0.5 g EDTA ✋

✋ Calcium chloride and EDTA are irritants. Be careful not to get them on your skin or inhale the powder.

1. Put on your safety goggles, and observe all the appropriate safety guidelines.
2. Label a beaker for each of the chemicals.
3. Measure out each chemical, and place each in the appropriate beaker.
4. Add 20 mL of water to each beaker, and stir using a clean glass stirring rod for each solution. Stir until all of the chemicals have dissolved.
5. Use the medicine dropper to slowly add 25 drops of the "lead" solution into the "blood" solution. Record your observations.
6. Pour all of the EDTA solution into the "blood" beaker. Record your observations.

A. What did you observe in Step 5? Explain your answer. T/I

B. What did you observe in Step 6? Explain your answer. T/I

C. What is the role of the excretory system in the treatment of lead poisoning? T/I

D. Based on what you know about excretion, which process do you think is involved? In what part of the nephron will the lead be removed? T/I

Kidney Disease

The kidneys must function properly to maintain water balance and homeostasis. Because the kidneys are in contact with all of the blood and wastes in the body, they are affected by disease or injury in other parts of the body. Conversely, any breakdown of kidney function has an impact on many other organ systems. Many kidney disorders can be diagnosed through urinalysis. In urinalysis, the contents of the urine are analyzed for traces of metabolites and molecules that result from disease.

CAREER LINK

Diabetes mellitus, which is caused by the insufficient secretion of insulin, causes the blood sugar level to rise. Most of the excess sugar remains in the nephrons, opposing the usual osmotic pressure maintained by active transport. The result is the retention of water, so patients with diabetes need to urinate more frequently. While some of the glucose can be excreted in the urine and can be detected by urinalysis, most of the excess glucose is reabsorbed in the proximal tubules of the nephrons.

Kidney stones are an affliction of the excretory system that is caused by the buildup of mineral solutes, such as oxalates, phosphates, and carbonates (**Figure 12**). These solutes can combine with calcium to produce crystals that accumulate and form stones. The sharp stones lodge in the renal pelvis or ureters and can cause considerable pain. Kidney stones are often broken up by high-energy sound waves in a process called extracorporeal shock wave lithotripsy (ESWL). They may also be removed with a uteroscope or by surgery.

The near total loss of kidney function requires the use of dialysis. In dialysis, the blood is run through a filtering machine, which acts as an artificial kidney. Total loss of kidney function leads to the need for a kidney transplant.

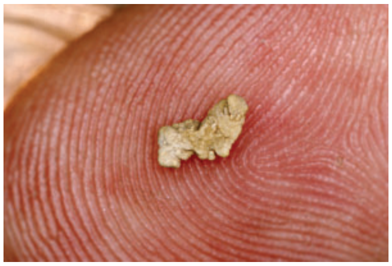


Figure 12 Buildup of minerals can form large deposits like this kidney stone.

Investigation **9.5.1**

Diagnosing Kidney Dysfunction (p. 457)

You have learned about some of the diseases that affect the kidneys and how they can be diagnosed by urine analysis. In this investigation, you will test simulated urine samples for physical or chemical properties that may indicate kidney dysfunction.

9.5 Review

Summary

- Single-celled organisms excrete waste directly to the environment. Most invertebrates have specialized structures to process and excrete waste.
- In mammals and other vertebrates, excretory tubules are found in the kidneys. The nephrons filter bodily fluids, reabsorb nutrients, and secrete urine.
- The Bowman's capsule and the glomerulus filter the blood. The fluid then moves through the proximal convoluted tubule, which actively reabsorbs ions and nutrients. Additional water is removed passively.
- The filtered blood reabsorbs water, ions, and other molecules, which are then absorbed in the peritubular capillaries.
- In the descending portion of the loop of Henle, water is reabsorbed by osmosis. In the ascending portion of the loop, ions are removed via active transport. In the distal convoluted tubule, the salt concentrations of the filtrate and the interstitial fluid are balanced.
- In the collecting duct, additional water is reabsorbed. The urine is collected in the renal pelvis. From there, it flows into the bladder, where it is stored until it is excreted.
- There are many diseases and disorders that can interfere with the proper functioning of the kidneys in excreting wastes and maintaining water balance.

Questions

1. (a) What are the similarities between the excretory organs of insects and the kidneys?
   (b) What are some of the differences? K/U
2. Victims of accidents and diseases are able to live healthy lives with just one kidney. With this in mind, what may be the reasons that the body normally uses two kidneys? T/I
3. Describe the flow of blood into and out of the kidneys. Compare the contents of the blood when entering and exiting the kidneys. K/U
4. Describe the flow of fluid through a nephron and to the external environment. Include a simple labelled sketch with your description. K/U C
5. Why is it beneficial for the nephrons to be so folded? K/U
6. You learned that 50 % of the urea is reabsorbed in the proximal convoluted tubes. Why does this not greatly concentrate the nitrogenous waste in the body? K/U
7. Using the Internet and other sources, research some ways to prevent the buildup of calcium. T/I
8. Using the Internet and other sources, research the relationship between diabetes and kidney function. What effect does diabetes have on the proper functioning of the excretory system? T/I
9. What would be the result on the body if Na^+, K^+, and Cl^- were not reabsorbed in the kidneys? K/U
10. How would running in hot temperatures, like Ray Zahab did, affect urine production? T/I
11. Use the Internet and other sources to research the condition known as proteinuria. In a brief summary, describe the causes, symptoms, and risks associated with this condition. T/I C
12. Using reputable sources, research the various causes of chronic kidney disease. Use your findings to answer the questions below. T/I
    (a) What are the causes and stages of chronic kidney disease?
    (b) What are the two types of dialysis, and what are the advantages and disadvantages of each?
    (c) What criteria must a patient meet to become a candidate for an organ transplant?
    (d) What are the issues involved in transplanting organs from a live donor versus a cadaveric donor? What are the risks involved with transplants?
13. Camels and kangaroo rats are just two examples of mammals that live in extremely arid environments. Use the Internet and other sources to find out more about the excretory systems of desert mammals. How are they able to conserve water and maintain proper kidney function? Report your findings back to the class. T/I C

WEB LINK

CHAPTER 9 Investigations

Investigation 9.2.1

CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating Homeostatic Feedback Mechanisms

Homeostasis is often maintained by negative feedback mechanisms. If the optimal functioning conditions of the body are upset by environmental changes, the body attempts to compensate through physiological and behavioural adjustments. Two common changes that may upset the body are a change in temperature and physical activity.

Testable Question

Part A: How does skin temperature respond to varying environmental conditions?
Part B: How does exercise affect breathing rate?

Prediction/Hypothesis

Part A: Based on your research and previous studies, predict how your skin temperature will change when exposed to various environmental conditions. Create hypotheses to explain your predictions.
Part B: Based on your research and previous studies, predict how your breathing rate will be affected by exercise. Create a hypothesis to explain your prediction.

Variables

Identify the independent and dependent variables in each part of the investigation, and identify the variables that should be controlled. Also identify the condition that serves as a control in each part of the investigation.

Experimental Design

In Part A of this controlled experiment, you will expose your skin to the following environmental conditions:

- dry skin in still room-temperature air
- dry skin in moving room-temperature air
- moist skin in still room-temperature air
- moist skin in moving room-temperature air
- skin inside warm clothing
- skin immersed in ice water

You will monitor how the temperature of your skin changes under these conditions and how long it takes for your skin to return to its normal temperature after being removed from the environmental stimuli.

In Part B, you will monitor how exercise affects your breathing rate, compare your findings to your resting breathing rate, and determine the time required for your breathing rate to return to normal after exercise.

Equipment and Materials

- alcohol thermometer
- non-contact Infra-Red (IR) thermometers or disposable temperature strips
- fan
- stopwatch
- large beaker or bowl
- thick winter glove
- body-temperature water (37 °C)
- ice

Procedure

SKILLS HANDBOOK A2.2

Part A: Temperature Regulation

1. Use an alcohol thermometer to measure the air temperature in the room.
2. Use the IR thermometer or a temperature strip to measure the temperature of the skin on the palm of your hand when it is exposed to still room-temperature air. Record this temperature, and identify it as the normal temperature.
3. Turn on the fan, and expose the palm of your hand to the moving air for 1 min. Turn off the fan, and measure and record the temperature of your skin. Measure and record the temperature after each 30 s interval, until your skin returns to the normal temperature.
4. Moisten the skin on the palm of your hand with body-temperature water. After 1 min, measure and record the temperature of your skin. Measure and record the temperature after each 30 s interval, until your skin returns to the normal temperature.
5. Moisten the palm of your hand again with body-temperature water, and expose it to moving air from the fan for 1 min. Turn off the fan, and measure and record the temperature of your skin. Measure and record the temperature after each 30 s interval, until your skin returns to the normal temperature.

6. Put on the winter glove. After 1 min, remove the glove and measure and record the temperature of your skin. Measure and record the temperature after each 30 s interval, until your skin returns to the normal temperature.
7. Fill the bowl with ice water. Immerse your hand in the ice water for 1 min. Remove your hand, and immediately measure the temperature of your skin. Measure and record the temperature after each 30 s interval, until your skin returns to the normal temperature.

Part B: Breathing Rate and Exercise

If you have a respiratory problem, or if there is any other medical reason why you should not participate in this investigation, inform your teacher. If you feel physically uncomfortable during the exercise part of this investigation, stop immediately.

8. Write a detailed procedure that you can use to measure your resting breathing rate, measure your breathing rate during an exercise activity, and determine how long your breathing rate takes to return to normal. Make sure that your procedure will allow you to test your hypothesis. Develop a data table to record your results. Have your teacher check and approve your procedure, and then carry out your procedure.

Analyze and Evaluate

Part A

(a) What variables were measured in this part of the investigation? What type of relationship was tested? T/I

(b) Graph your results with appropriate labels. What trends do you see in your results? T/I C

(c) Did the time required to return to normal skin temperature differ under the different conditions? Why or why not? T/I

(d) Which condition produced the greatest change in skin temperature? Is this what you expected? Explain. T/I

(e) Compare your results with the predictions you made before the investigation. Do your observations agree with your predictions? Why or why not? T/I

(f) Identify any possible sources of error. How could these be eliminated to ensure more accurate data? T/I

(g) Do you think that others would observe the same results if they carried out the same investigation? Why or why not? T/I

Part B

SKILLS HANDBOOK A5.4

(h) Graph your results, and describe the trends illustrated by the data. T/I C

(i) Do your observations support your hypothesis? Explain your answer. T/I

Apply and Extend

(j) Describe how this investigation illustrated homeostatic feedback mechanisms. T/I

(k) Did you observe negative or positive feedback mechanisms? Explain your answer. T/I

(l) How do you think the results in Part A would have been different if the air temperature in the room had been higher or lower? T/I

(m) Based on your results in Part A, suggest measures that could be taken to help maintain a constant body temperature. T/I

(n) In Part B, you examined how your breathing rate changed in response to exercise. What might be another response of the respiratory system to exercise? A

(o) Use the Internet and other sources to research the recovery rate as an indicator of physical fitness. Summarize the results of your research in a brief report. T/I C

(p) Compile the data for Part B obtained by all the students in your class. Analyze the data for any differences in breathing rate changes and recovery that are based on age, height, gender, and other variables. Summarize the results of your analysis. T/I C

WEB LINK

Investigation 9.5.1 ACTIVITY

Diagnosing Kidney Dysfunction

Do you know someone who has diabetes? How was the condition diagnosed? Urinalysis is a simple and effective method of testing for a variety of kidney and related disorders. These disorders include diabetes mellitus, diabetes insipidus, Bright's disease, and calcium oxalate and calcium carbonate kidney stones.

Diabetes mellitus is characterized by the presence of glucose and ketones in the urine. Diabetes insipidus is characterized by the inability of the body to retain water, which results in the excretion of large volumes of dilute urine. The specific gravity of the urine is lower than normal. (The specific gravity of a liquid is the ratio of the density of that liquid to the density of water (1 g/mL).) The presence of protein in the urine suggests that the patient suffers from nephritis or Bright's disease. Acidic urine is usually associated with the formation of calcium oxalate kidney stones. Alkaline urine is usually associated with the formation of calcium carbonate, calcium phosphate, and magnesium phosphate kidney stones.

The purpose of this activity is to help you understand how urinalysis data can be used as a tool to diagnose kidney disorders and other disorders. This activity is not intended to train you to interpret the results of urinalysis. Interpretation of urinalysis results is a complex and difficult skill that should be done only by trained and qualified specialists.

Purpose

In this activity, you will determine the physical and chemical characteristics of samples of simulated urine and analyze the results to diagnose possible kidney disorders or other disorders.

Equipment and Materials

- lab apron
- waterproof latex or nitrile gloves
- urinalysis reference ranges
- urine test strips to test for glucose, ketones, protein, pH, and specific gravity
- simulated urine samples

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Procedure

1. Label the samples of simulated urine as Samples 1, 2, 3, and 4. Create a data table for the factors you will be testing.
2. Put on your lab apron and protective gloves.
3. Carefully follow the instructions provided with the test strips. Immerse a fresh strip into each sample.
4. Record your results for each test.
5. Use the information available in the introduction and the urinalysis references to analyze the results of your tests. You may find additional information on reputable websites. 🌐

Analyze and Evaluate

(a) Present a possible diagnosis for each of your test results. T/I

(b) Explain the importance of test strip diagnosis. T/I

(c) How confident are you in making a diagnosis on the basis of your tests? Explain. T/I

Apply and Extend

(d) Choose one of the disorders you tested for, and conduct additional research about this disorder. Investigate the symptoms, causes, and treatments of this disorder, and summarize your findings in a brief report. 🌐 T/I C

(e) Further tests showed the presence of ketones in the urine of a patient. Doctors determined that the patient did not have diabetes. Use the Internet and other sources to research other possible conditions that might lead to the presence of ketones in the urine. 🌐 T/I

(f) Why is nephritis difficult to treat? Use the Internet and other sources to find possible reasons. 🌐 T/I

🌐 WEB LINK

CHAPTER 9 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 426. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 426. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

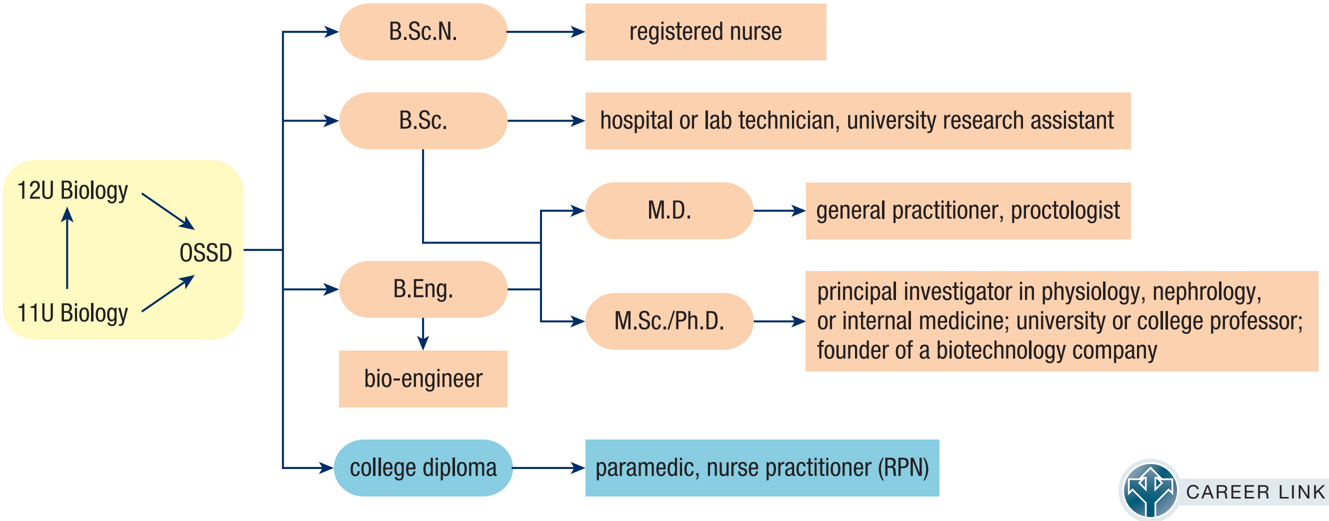
homeostasis (p. 428)
internal environment (p. 429)
interstitial fluid (p. 429)
homeostatic mechanism (p. 430)
negative feedback (p. 432)
sensor (p. 432)
integrator (p. 432)
set point (p. 432)
effector (p. 432)
positive feedback (p. 434)
thermoregulation (p. 436)
homeotherm (p. 437)
poikilotherm (p. 437)
endotherm (p. 437)
ectotherm (p. 437)
thermal acclimatization (p. 438)
torpor (p. 439)
hibernation (p. 440)
estivation (p. 440)
osmotic pressure (p. 442)
hyperosmotic (p. 442)
hypoosmotic (p. 442)
isoosmotic (p. 442)
osmoregulation (p. 443)
contractile vacuole (p. 446)
metanephridium (p. 446)
Malpighian tubule (p. 447)
nephron (p. 448)
Bowman's capsule (p. 449)
glomerulus (p. 449)
afferent arteriole (p. 449)
efferent arteriole (p. 449)
peritubular capillaries (p. 449)
proximal convoluted tubule (p. 449)
loop of Henle (p. 449)
distal convoluted tubule (p. 449)
filtration (p. 451)
reabsorption (p. 451)
aquaporin (p. 451)
secretion (p. 452)

CAREER **PATHWAYS**

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to homeostasis that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.


12U Biology
11U Biology
OSSD
B.Sc.N.
registered nurse
B.Sc.
hospital or lab technician, university research assistant
M.D.
general practitioner, proctologist
B.Eng.
bio-engineer
M.Sc./Ph.D.
principal investigator in physiology, nephrology, or internal medicine; university or college professor; founder of a biotechnology company
college diploma
paramedic, nurse practitioner (RPN)

CAREER LINK

CHAPTER 9 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which term refers to the tendency of organisms to maintain a stable internal environment? (9.1) K/U
   (a) physiology
   (b) micro-anatomy
   (c) neutralization
   (d) homeostasis
2. How does the nervous system help to maintain homeostasis? (9.1) K/U
   (a) It regulates the levels of various hormones that are essential to life processes.
   (b) It protects the body from infections and fights infections.
   (c) It receives data from the environment and transmits signals throughout the body.
   (d) It carries hormones and chemicals throughout the body.
3. What is the primary mechanism of homeostasis? (9.2) K/U
   (a) positive feedback loop
   (b) negative feedback loop
   (c) set point
   (d) effector
4. Which term refers to animals that maintain a constant body temperature? (9.3) K/U
   (a) ectotherms
   (b) homeotherms
   (c) endotherms
   (d) poikilotherms
5. During which season is an animal most likely to enter a state of estivation? (9.3) K/U
   (a) spring
   (b) summer
   (c) autumn
   (d) winter
6. Which of the following best describes a hyperosmotic solution? (9.4) K/U
   (a) a solution with a higher concentration of solutes on one side of a selectively permeable membrane
   (b) a solution with a lower concentration of solutes on one side of a selectively permeable membrane
   (c) a solution with the same solute and water concentrations on both sides of a selectively permeable membrane
   (d) none of the above
7. If two solutions have equal concentrations of water, what are they called? (9.4) K/U
   (a) hyperosmotic
   (b) hypoosmotic
   (c) isoosmotic
   (d) thermoregulated
8. Which structure do free-living single-celled organisms use to maintain osmotic balance? (9.5) K/U
   (a) metanephridia
   (b) Malpighian tubules
   (c) nephrons
   (d) contractile vacuoles
9. What are the functional units of the kidney? (9.5) K/U
   (a) peritubular capillaries
   (b) nephrons
   (c) Bowman's capsule
   (d) glomerulus

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. Homeostasis is the process in which animals maintain an external environment that promotes proper cellular functioning. (9.1) K/U
11. Negative feedback occurs when a system responds to change by attempting to compensate for this change. (9.2) K/U
12. Positive feedback mechanisms enhance the effect of a change in either the internal or external environment and usually result in homeostasis. (9.2) K/U
13. Endotherms are animals that regulate their body temperature with internal mechanisms of thermal energy conservation and dissipation. (9.3) K/U
14. The endocrine system, whose major organs are the liver and the kidneys, removes nitrogenous wastes, excess water, and toxic compounds from the body. (9.4) K/U
15. All animals produce waste nitrogen in the same form. (9.4) K/U
16. Urine is formed within the glomerulus, which is the functional unit of the kidney. (9.5) K/U
17. Urine flows from the proximal convoluted tubule to the collecting duct, where additional water is absorbed. (9.5) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. "The human body can regulate its internal environment and maintain stable conditions suitable for essential biological processes." Which comment about this statement is correct? (9.1) K/U
   (a) It refers only to the physiology of the circulatory system.
   (b) It refers to homeostasis in the body.
   (c) It explains how positive feedback mechanisms work.
   (d) It refers to the direct control of cellular activities by nucleic acids.
2. Which body function is performed by the endocrine system? (9.1) K/U
   (a) regulating the levels of various hormones essential to life processes
   (b) protecting the body from infections and fighting infections
   (c) receiving data from the environment and transmitting signals throughout the body
   (d) carrying hormones and chemicals throughout the body
3. What is the correct order of the three components of homeostatic mechanisms? (9.2) K/U
   (a) sensor, integrator, effector
   (b) sensor, effector, integrator
   (c) effector, integrator, sensor
   (d) integrator, sensor, effector
4. If human body temperature drops below the set point, the hypothalamus activates effectors. What do these effectors induce? (9.2) K/U
   (a) vasodilation
   (b) vasoconstriction
   (c) vasopressin
   (d) vasospasm
5. Which of the following best describes conduction? (9.3) K/U
   (a) the transfer of thermal energy within a fluid
   (b) the transfer of thermal energy in the form of electromagnetic radiation
   (c) the flow of thermal energy between molecules that are in direct contact with each other
   (d) the flow of thermal energy in water only
6. Which of the following best describes torpor? (9.3) K/U
   (a) a sleeplike state where metabolic rate and body temperature drop in response to variations in daily temperature
   (b) a sleeplike state where metabolic rate and body temperature rise in response to variations in daily temperature
   (c) a state of inactivity and significantly decreased metabolic rate
   (d) a state of increased activity and metabolic rate
7. Which substance is a by-product of deamination and is highly toxic to the body? (9.4) K/U
   (a) urea
   (b) ammonia
   (c) nitrogen
   (d) carbon
8. When urine flows from the kidney to the urinary bladder, which structure does it flow through? (9.5) K/U
   (a) urethra
   (b) proximal tubule
   (c) medulla
   (d) ureter
9. Which fluid enters the glomerulus? (9.5) K/U
   (a) serum
   (b) blood
   (c) water
   (d) glucose

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. One example of a homeostatic mechanism is the regulation of body temperature. (9.1) K/U
11. Homeostasis is a constant condition that rarely changes. (9.1) K/U
12. The set point is the minimum value of a given variable of a system. (9.2) K/U
13. Signals from the hippocampus are what enable humans to sense a lowered body temperature. (9.2) K/U
14. Both ectotherms and endotherms have behavioural mechanisms that regulate their body temperature. (9.3) K/U
15. Thermal acclimatization is the instantaneous adjustment to seasonal variations in temperature. (9.3) K/U
16. Thermoregulation ensures that the intracellular and extracellular fluids are isoosmotic. (9.4) K/U
17. Reabsorption refers to the process in which fluid and small molecules pass into the Bowman's capsule. (9.5) K/U

Match each term on the left with the most appropriate description on the right.

18. (a) Bowman's capsule
    (b) glomerulus
    (c) nephron
    (d) ureter
    (e) urethra

    (i) very tiny filtration units in the kidney
    (ii) tube that leads from the kidney to the urinary bladder
    (iii) cuplike capsule around the glomerulus of the kidney
    (iv) tube that carries waste away from the bladder
    (v) group of blood-circulating capillaries (9.5) K/U

19. (a) loop of Henle
    (b) proximal tubule
    (c) urea
    (d) renal artery
    (e) kidney

    (i) major organ of excretion
    (ii) waste product that is high in nitrogen and is found in the urine
    (iii) blood vessel that carries blood to the kidney
    (iv) part of the system of tubules that filtrate passes through; joins the proximal convoluted tubule and the distal convoluted tubule in the nephron
    (v) structure that carries filtrate from the Bowman's capsule to the loop of Henle (9.5) K/U

Write a short answer to each question.

20. In your own words, define "homeostasis." (9.1) K/U
21. Explain why it is important for organisms to maintain homeostasis. (9.1) K/U
22. Identify the components of a typical feedback loop, and describe the role of each component. (9.2) K/U
23. Develop a graphic organizer to compare and contrast positive and negative feedback. Include an example of each type of feedback. (9.2) K/U C
24. Frogs are best described as poikilotherms. Explain why. (9.3) K/U
25. Ectotherms have an advantage over endotherms in terms of energy requirements. Explain this advantage. (9.3) K/U
26. How do shivering and "goose bumps" help to maintain homeostasis? (9.3) K/U
27. Identify two factors that influence whether osmosis occurs, and explain how each factor works. (9.4) K/U
28. Describe turgor pressure, and explain why it is particularly important in plant cells. (9.4) K/U
29. What are the three forms of nitrogenous waste that are produced by animals? (9.4) K/U
30. Describe how metanephridia are different from Malpighian tubules. (9.5) K/U
31. Describe the structure and function of the nephron. (9.5) K/U
32. Describe aquaporins, and explain their function. (9.5) K/U
33. What causes filtrate to cross from the capillaries of the glomerulus to the Bowman's capsule? (9.5) K/U
34. Examine **Figure 1**. (9.5) K/U

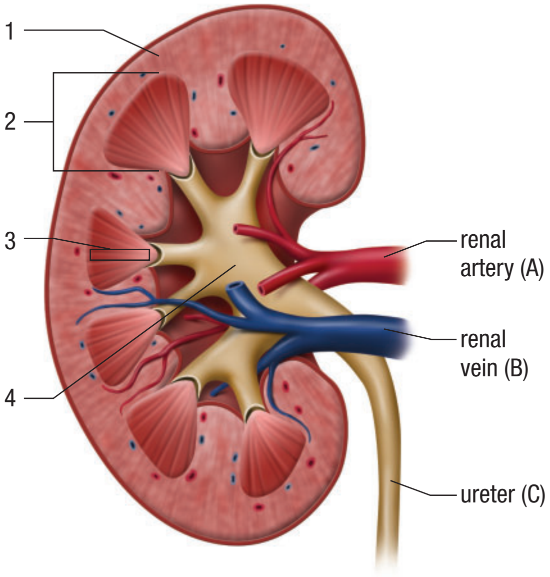


Figure 1

    (a) Identify the structures numbered 1 to 4.
    (b) Which structure would contain the least amount of waste: A, B, or C?
    (c) Name the structure in which filtration occurs.

Understanding

35. Identify three organ systems, other than the excretory system, that are involved in homeostasis, and describe the role of each system. (9.1) K/U
36. Explain how sweating results from a negative feedback mechanism. (9.2) K/U
37. Give an example of a positive feedback mechanism in the human body. (9.2) K/U A
38. List and define four mechanisms of heat loss. (9.3) K/U
39. Compare and contrast thermoregulation in endotherms and ectotherms. (9.3) K/U
40. Explain the difference between torpor and hibernation. (9.3) K/U

41. Explain the specialized thermoregulatory adaptation exhibited by the jackrabbit in **Figure 2**. (9.3) K/U

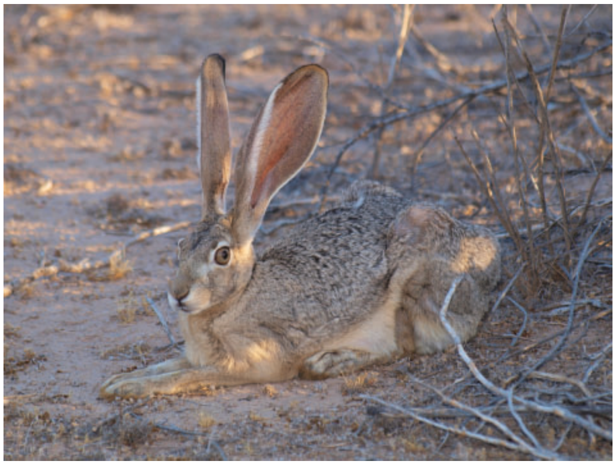


Figure 2 A long-eared jackrabbit

42. (a) Define "osmoregulation."
    (b) Name an organ that that performs osmoregulation and excretion. (9.4, 9.5) K/U

43. What are nitrogenous wastes? (9.4) K/U

44. List the three main types of nitrogenous wastes that are excreted by organisms. (9.4) K/U

45. Identify the main nitrogenous waste that is produced by humans, and describe how it is produced. (9.4) K/U

46. Name and explain the three interrelated processes that result in the formation of urine. (9.5) K/U

47. Based on what you have learned about hibernation, do you think that bears in a zoo hibernate? Explain why or why not. (9.3) K/U A

48. A certain cell has a membrane that is permeable to water, but not to Na^+, Cl^-, or any other solute. There is more NaCl outside the cell than there is inside the cell. Describe the movement of substances into and out of the cell. Explain your answer. (9.4) K/U T/I

49. What two factors, other than osmotic and hydrostatic pressure, can influence the rate at which water flows across a membrane? Explain the mechanism for each factor. (9.4) K/U T/I

Analysis and Application

50. An animal has excretory tubules with a closed proximal end that is immersed in hemolymph and a distal end that empties into the gut. (9.5) K/U T/I
    (a) What term would you use to describe these tubules?
    (b) What type of nitrogenous waste would be excreted from these tubules?

51. A runner is sweating heavily on a hot summer day. She forgot her water bottle and has no access to water. As a result, the following feedback loop occurs:
    - There is a decrease in the blood plasma, so the solute concentration of the blood increases. This causes both the blood volume and the blood pressure to decrease.
    - Osmoreceptors sense the increased solute concentration, decreased blood volume, and decreased blood pressure.
    - The hypothalamus sends messages to the posterior pituitary gland to increase the release of ADH (the hormone that controls water balance).
    - An increased level of ADH causes the kidneys to reabsorb more water and to release less water in the urine.
    - Reabsorbed water in the blood increases the blood volume, increases the blood pressure, and decreases the solute concentration.
    - Information regarding the changes in blood volume, blood pressure, and solute concentration is sent to the hypothalamus.

    Draw a flow chart, with appropriate labels and directional arrows, for this negative feedback loop. Use ↑ for "increases," ↓ for "decreases," and → for "leads to" or "yields." (9.1, 9.2, 9.4, 9.5) K/U T/I C

52. (a) Why do you think doctors ask patients for a urine sample as part of an annual physical examination?
    (b) Suggest two conditions or illnesses that could be detected through urinalysis. (9.5) K/U T/I

53. Explain the common recommendation to drink six to eight glasses of water per day. (9.4, 9.5) K/U T/I

54. How would the volume and characteristics of urine change for each of the following people? (9.4, 9.5) K/U T/I A
    (a) a soccer player after playing a game in hot weather
    (b) a person who had been consuming alcohol for several hours
    (c) a person who had consumed a litre of water after moderate exercise

55. Proteinuria refers to the presence of serum proteins in the urine. Explain why proteinuria would be considered a sign of damage or injury to the glomerulus. (9.5) K/U T/I

56. Hematuria is another symptom of renal disease, but it is less specific to the kidneys. Why do you think this is? (9.5) K/U T/I

57. Why does the ingestion of coffee or colas increase urination? (9.4, 9.5) K/U T/I

58. **Table 1** shows the partial results of urinalysis for two samples. (9.5) K/U T/I A

Table 1

Property	Normal value	Sample 1	Sample 2
colour	straw yellow to golden amber	yellow	reddish-brown
specific gravity	1.001 to 1.028	1.015	1.050
pH	4.6 to 8.0	4.5	6.5
protein	low to none	none	none
glucose	less than 0.03 g/100 mL	0.10	0.01
ketones	none	present	none
leukocytes	few	none	none
blood	low to none	none	none

(a) Compare the values for each sample against the normal values, and suggest a possible diagnosis (disease or disorder). Explain your reasoning.

(b) If glucose filters through the glomerulus, why is glucose not usually found in urine?

(c) Ketones are usually produced by the liver as part of fatty acid metabolism. The ketones will be completely metabolized so that very little, if any at all, appear in the urine. If the body cannot get enough glucose for energy, it switches to using body fats for energy. This results in an increase in ketone production, making ketones detectable in the blood and urine. Ketones are sometimes seen in the urine of a patient with poorly controlled diabetes. What other reason could cause ketones to be seen in the urine or blood?

59. The process of making coffee can be compared with one of the processes in excretion (**Figure 3**). (9.5) K/U T/I

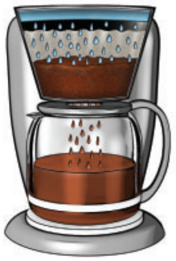


Figure 3

(a) What process in excretion could Figure 3 represent?

(b) Where in the nephron would this process occur?

(c) What substances in human blood could be compared to the coffee grounds left in the filter?

(d) Compare the process that is used to make coffee with the process of urine formation, in terms of what is retained and what is discarded.

60. The expression "crying crocodile tears" means pretending to be sad or sorry when you really are not sad or sorry. The idea comes from the ancient belief that crocodiles cried while luring or eating their prey. Explain the truth behind this belief. (In other words, why do crocodiles really "cry"?) (9.5) K/U T/I

61. Amphibian larvae excrete ammonia, but adult amphibians excrete urea. Account for this difference. (9.5) K/U T/I

Evaluation

62. For more than 70 years, researchers have known that the hormone oxytocin is needed for mammals to have a healthy birth. A synthetic form of oxytocin, called Pitocin, is often administered to women during labour, creating a positive feedback loop. Why do you think this is done? (9.2) T/I A

63. In medicine, the loss of normal thermoregulation in humans is referred to as poikilothermia. For example, most people who have complete spinal cord injuries are not able to sweat below the level of the injury, and many people who are quadriplegic cannot sweat even above the point of injury (although they may sweat due to autonomic dysreflexia, which is an overreaction of the nervous system). (9.3) K/U T/I A

(a) Use your current knowledge to make a prediction about how this could affect their ability to thermoregulate.

(b) How could you warm or cool (that is, normalize the core temperature of) a person with a spinal cord injury?

(c) Why do you think this condition is called poikilothermia?

64. Imagine that you and a friend are stranded on a desert coastline. It is incredibly hot. You are sweating profusely and desperate for a drink. Lack of food and sunburn are the least of your worries. Dehydration is rapidly becoming a stark reality. In front of you are millions of gallons of seawater. Your friend insists that a little seawater will not hurt you, and that drinking seawater is better than dying of dehydration. While you wait to be rescued, explain each of the following to your friend. Use diagrams to support your explanation. (9.3, 9.5) K/U T/I C A

(a) how the human body absorbs water

(b) why we cannot drink large amounts of pure water

(c) why we cannot drink seawater or salt water

(d) why drinking salt water when dehydrated is absolutely the worst thing you can do

65. Why do the cells of the nephron tubules have high numbers of mitochondria? (9.5) K/U T/I

66. When doctors treat a patient with diabetes, they often examine the patient's urine, as well as the patient's blood glucose level. Provide a possible reason why doctors examine a patient's urine. Justify your reasoning. (9.5) K/U T/I

67. A classmate tells you that the only purpose of the kidneys is to filter blood. (9.5) K/U T/I C
    (a) Is your classmate correct? Justify your reasoning.
    (b) How would you respond to your classmate?

68. A hormone called atrial natriuretic factor (ANF) is produced by the right atrium of the heart. It stimulates the excretion of sodium and water by the kidneys and helps to regulate blood pressure. Propose an evolutionary reason why the heart would secrete a hormone that regulates renal function. (9.5) K/U T/I

69. An expectant mother excretes nitrogenous wastes through her urine. How does the fetus excrete nitrogenous wastes? (9.4, 9.5) T/I

70. Why would infants be more susceptible to dehydration than adults? (9.3, 9.5) K/U T/I

71. Some prescription drugs, such as those that relieve allergies, can make the body more sensitive to heat because they prevent the body from sweating. What would someone who is taking one of these drugs need to keep in mind or be more careful about? (9.3, 9.5) K/U T/I A

Reflect on Your Learning

72. Urine testing and anti-doping have become a common part of international sports competitions. T/I
    (a) Why do you think this type of testing is necessary?
    (b) Do you believe this type of testing will stop the problem of drug abuse? Justify your answer.
    (c) Do you think athletes should have the option of refusing or requesting urine testing? Explain.

73. In many parts of the world, laws ban the sale of human organs. Unfortunately, in some countries, people sell their organs for money. One desperate neighbourhood in India is known locally as "kidney village" because so many of its residents have sold one of their kidneys. Recipients pay as much as \$100 000 for a black market kidney. Donors receive a fraction of this amount, but it is still a substantial sum to people who desperately need the money. T/I
    (a) Do you believe that selling organs is an acceptable practice? Explain your answer.
    (b) If you or someone close to you needed an organ for transplant, and you had enough money, would you consider buying an organ? Why or why not?

74. Scientific research has resulted in many improvements in the field of transplantation, to the point that most transplant operations are now considered low risk. For example, kidney transplants have a high success rate. A main limitation of transplant operations, however, is that they rely on organ donation. T/I
    (a) Do you know anyone who has had transplant surgery or needs transplant surgery? If so, has this changed how you feel about organ donation? Explain.
    (b) Would you agree to donate an organ, such as a kidney? Describe the feelings you have when you think about being an organ donor.
    (c) What questions about organ donation or transplantation would you like to have answered before making a decision?
    (d) How could you get these questions answered? Suggest three possible sources for answers.

Research

WEB LINK

75. Freedivers have trained their body and mind to function underwater for long periods of time without taking a breath, thanks to a phenomenon called the mammalian diving reflex (**Figure 4**). An Austrian freediver named Herbert Nitsch has reached a record depth of 214 m on one breath!

Figure 4 A freediver in Bonaire

Using the Internet and other sources, research the mammalian diving reflex and answer the following questions:
    (a) What is the mammalian diving reflex? What purpose does it serve?
    (b) Describe the three processes that are triggered in the order in which they occur.
    (c) How does the mammalian diving reflex differ from hypothermia? K/U T/I

76. Research glomerulonephritis. Share your findings in the format of your choice. Include answers to the following questions:
    - What is glomerulonephritis?
    - Is there another name for this disease?
    - What are the risk factors, symptoms, treatment, and prognosis for people who suffer from this disease? T/I C

77. Transplantation is a highly successful procedure for treating a variety of human illnesses. However, the number of transplants that can be performed is limited by the availability of human organs and tissues. Xenotransplantation is one possible way to relieve the ongoing shortage of human organs. It offers a large supply of organs, tissues, and cells for transplantation.

Use the Internet to research xenotransplantation, and write a one- to two-page report to summarize your findings. Present your report to your classmates. Use the following questions as a guide:

- What is xenotransplantation?
- What are the potential benefits and drawbacks of xenotransplantation?
- Have animal organs or tissues ever been used for transplantation? Explain why or why not.
- What is the regulatory status of xenotransplantation in Canada?
- Do you think it is acceptable to use animals in this way? Explain your answer.
- Would you consider having an animal organ transplant if a human organ were not available? Explain your answer. K/U T/I C

78. Gout is a painful rheumatic disease. It causes inflammation and acute intermittent pain in the joints of the feet, knees, ankles, hands, and wrists. It often starts in the feet or toes. In fact, for 70 % of sufferers, a joint in the big toe is the first to be affected. Gout mainly affects men between 40 and 60 years of age, but adult men and women of all ages can suffer from gout. Recent research has indicated that, among other factors, alcohol use is strongly associated with the increased incidence of gout.

Use the Internet and other sources to research gout and to investigate how people can minimize (or avoid) this condition. Create a pamphlet or a poster that explains the causes and symptoms of gout, as well as ways that people can avoid the pain of the acute attacks. Use the following questions to guide your research:

- What is gout?
- Why is gout considered to be a disease of the excretory system?
- Why do medical researchers believe that drinking can lead to gout?
- Which form of alcohol seems to be the worst offender, and why?
- What other factors increase the number and severity of gout attacks?
- How can people prevent gout attacks? T/I

79. Heat exhaustion and heatstroke occur when the body's thermoregulatory responses are inadequate to preserve homeostasis. They can result from outside factors that make heat dissipation less efficient, such as extremes of temperature, physical effort, and environmental conditions. They can also result from internal factors that often put children, elderly people, and those who have pre-existing medical conditions at increased risk.

In your summer job at a weather station, you have been asked to put together a public service video, poster, or pamphlet to help inform the general public about heat exhaustion and heatstroke. You have been asked to answer the following questions in your public service product:

- What are heat exhaustion and heatstroke?
- Who is most susceptible?
- What are the signs and symptoms to watch out for?
- How can you avoid heat exhaustion and heatstroke?
- What should you do if someone exhibits any signs or symptoms of heat exhaustion or heatstroke?

Present your final product to your classmates. K/U T/I C

80. Humans and other endothermic animals are designed to maintain a relatively constant body temperature of approximately 37 °C. If they are frozen, their internal fluids turn to ice, damaging or killing cells and tissues. Wood frogs, however, can become "frogsicles" (**Figure 5**) in the winter and thaw out in the spring, with no internal damage.

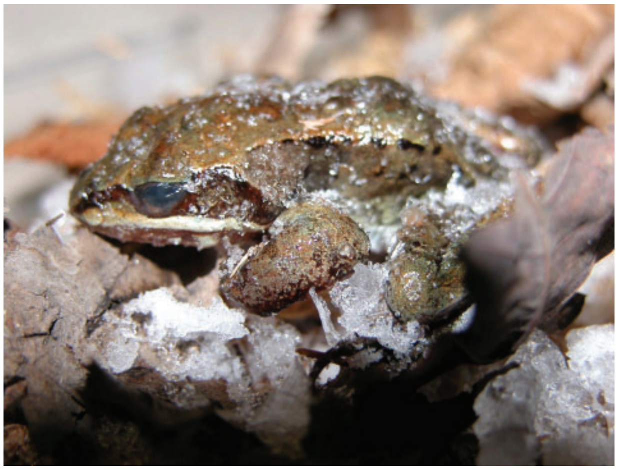


Figure 5 A frozen wood frog

Ken and Janet Storey at Carleton University in Ottawa have spent more than 20 years identifying the genetic switches and biochemical processes that allow wood frogs to freeze. Use the Internet and other sources to investigate their work. Report your findings in a short newspaper-style article. K/U T/I C

CHAPTER

10 The Endocrine System

KEY CONCEPTS

After completing this chapter you will be able to

- identify hormones as chemicals that are released in one part of the body and affect cells in other parts of the body
- identify various endocrine glands inside the body, the hormones they produce, and how some of them are controlled by the pituitary gland
- describe how the thyroid and parathyroid glands produce hormones that regulate the body's metabolism
- describe how diabetes is a condition in which the blood sugar level is no longer regulated due to the inability of the endocrine system to produce or use insulin
- recognize that steroids are natural hormones, but their misuse can have serious adverse health effects
- explain how sex hormones regulate male and female reproductive development and cycles
- explain how environmental contaminants can mimic the actions of hormones

How Do Hormones Help to Maintain Homeostasis?

Perhaps you know someone who has diabetes. Diabetes is a common endocrine condition in which sugar levels in the blood are not properly regulated due to insufficient secretion and/or action of the hormone insulin. People with diabetes often need to check their blood sugar level several times a day by testing their blood with a special meter called a glucometer. They may need to inject themselves with insulin to control their blood sugar level or use a pump that automatically delivers insulin to their bloodstream.

Chris Jarvis is an Olympic rower from Grimsby, Ontario, who has type 1 diabetes and is dependent on insulin. Diagnosed at age 14, Chris did not let his diabetes disrupt his pursuit of athletics. He learned how to test his blood sugar level and administer insulin to keep his body performing competitively. Chris discovered rowing in high school, was captain of his rowing team in university, and became a world-class athlete competing for Canada in the 2004 Olympics. By understanding how his body works and learning how to control his insulin and blood sugar level with the help of the latest technology, Chris has been able to live an active life and represent his country on the world stage.

The human body is a complex system of specialized organs and chemical processes that need to be regulated so they can work together to maintain homeostasis. Many of the functions of the body's systems are controlled by two interacting systems: the endocrine system and the nervous system. The nervous system senses internal and external stimuli and responds by sending electrical signals throughout the body. Some stimuli cause a response from the endocrine system, which consists of glands and the hormones they produce. Hormones are chemical messengers that control body processes. Together, the nervous system and the endocrine system maintain homeostasis. When the endocrine system malfunctions, the result can be the overproduction or underproduction of a hormone. Hormonal imbalance can interfere with the normal functions of many of the body's systems, including the circulatory, digestive, nervous, and reproductive systems.

A better understanding of the endocrine system will help you guard your own health. In this chapter, you will become aware of the symptoms of common endocrine disorders. You will learn the effects of synthetic hormones: how they are used therapeutically in a medical setting and how they can be abused. Finally, you will become aware of the delicate and constant balancing act that is performed by your endocrine system to keep your body in a state of homeostasis in an ever-changing environment.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. What is a hormone? Name as many as you can.
2. Why might a person use a synthetic hormone?
3. What hormones are considered drugs of abuse? What are their desired effects and harmful effects?
4. What are the roles of hormones during puberty?
5. What diseases are associated with hormone problems?

Mini Investigation

Analyzing Human Growth

Skills: Observing, Analyzing, Evaluating

SKILLS HANDBOOK **A2.1, A5.4**

There are many hormones, with many different effects on your body. Sex hormones and growth hormones are the most conspicuous. Males and females have different growth patterns starting at puberty and extending to adulthood.

Males and females develop at slightly different rates, and they go through growth spurts in height at different times. **Table 1** summarizes the average heights for Canadian male and female youth from birth to age 19.

Table 1 Average Height of Canadian Children and Teenagers by Sex

Age (year)		birth	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Height (cm)	**female**	49	74	86	95	103	109	115	121	127	133	139	145	151	157	160	162	163	163	163	163
	male	50	76	88	96	103	110	116	122	127	133	138	143	149	156	163	169	173	175	176	177

Equipment and Materials: graph paper; coloured pencils or pens; spreadsheet software (optional)

1. Use the information in Table 1 to construct line graphs for the average heights of females and males on the same set of axes. Use a different colour to represent each sex.

A. What trends or patterns in the growth of males and females do you observe? T/I

B. About how long does it take a newborn to double in height? T/I

C. At what ages do females grow more rapidly than males? At what ages do males grow more rapidly? T/I

D. Propose an explanation for the variations in growth rates that you observed in the data. T/I A

E. What other changes in female and male bodies occur during the periods of significant growth? What do you think accounts for these changes? T/I A

10.1 Hormones: Chemical Regulators

Puberty brings about many changes in the human body. Both males and females experience a growth spurt during puberty, and the secondary sex characteristics begin to develop. Males experience the growth of body and facial hair, a deepening of the voice, and the development of the genitals. Females experience the growth of body hair, the onset of their menstrual cycle, and the development of breasts and broader hips.

All of these developments of puberty are timed and controlled by hormones: chemicals produced by cells in one part of the body that regulate the processes of cells in another part of the body. Hormones act as chemical messengers, enabling one part of the body to give instructions to another part. Other chemicals, called local regulators, are like hormones but act on nearby cells, rather than cells some distance away. Some cells even self-regulate, producing chemicals to stimulate their own cellular processes.

Hormones are secreted by the cells, tissues, and organs that compose the endocrine system. The endocrine system, like the nervous system, regulates and coordinates the functions of organs throughout the body. In this way, the endocrine system contributes to the control of growth, development, reproduction, behaviour, energy metabolism, and water balance. The nervous and endocrine systems are structurally, chemically, and functionally related, but they control organ and tissue functions in different ways. The nervous system sends fast electrical signals along the nerves. The speed of these nerve impulses enables an organism to interact rapidly with its external environment. The endocrine system uses hormones, with slower, longer-acting responses, to control organ and tissue functions. Of course, the endocrine system itself has to be controlled, so that hormones are released when needed. Because the nervous system can regulate the release of most hormones, it ultimately controls the actions of the endocrine system.

Endocrine glands are ductless secretory organs that secrete their hormones directly into the blood or extracellular fluid. (In contrast, exocrine glands, such as the sweat and salivary glands, release their secretions into ducts that lead outside the body or into the body cavities.) The hormones are then circulated throughout the body in the blood and other body fluids. As a result, most body cells are constantly exposed to a wide variety of hormones. Only target cells, however, will respond to a specific hormone because only they have receptor proteins that recognize and bind to that type of hormone (**Figure 1**). Hormones are cleared from the body at a steady rate by enzymatic breakdown in their target cells, in the blood, or in organs such as the liver or kidneys. The breakdown products are reused or excreted.

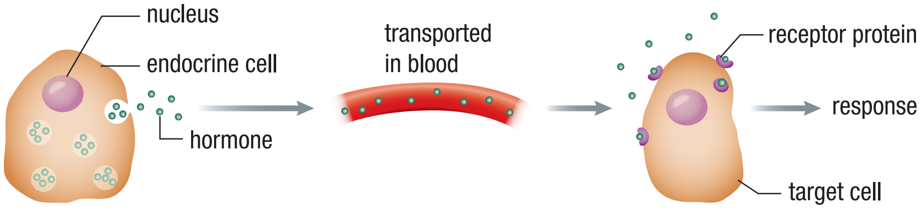


Figure 1 Hormones are produced by the cells of the endocrine glands and released into the bloodstream, where most of the body cells are exposed to them. Only the target cells with the appropriate receptor proteins respond to a hormone.

In this section, you will consider the nature of hormones, the way they work, and their importance in the normal functioning of the body and the maintenance of homeostasis.

Types of Hormones

There are more than 60 known hormones and local regulators in humans. Many are identical or very similar in structure and function to the hormones in other animals, although many animals have hormones not found in humans. Hormones are identified by their chemical structure. There are two main types: protein hormones, which are water soluble, and steroid hormones, which are lipid soluble. Most hormones fall into one of these two types.

Protein hormones consist of amino acid chains, ranging in length from as few as 3 amino acids to more than 200. They are released into the blood or extracellular fluid by the cells in the endocrine glands where they are produced. Protein hormones are usually hydrophilic: they have an affinity for water and diffuse well through the blood and intercellular fluids. One group of protein hormones, the growth factors, regulates the division and differentiation of many types of cells in the body.

protein hormone a hormone composed of chains of amino acids that is water soluble; usually acts on cell membrane receptors

Steroid hormones are derived from cholesterol and are not very soluble in blood. However, they can pass easily through the lipid bilayer of cellular membranes. Steroid hormones can combine with hydrophilic carrier proteins to form water-soluble complexes, which allow them to diffuse easily into blood and other fluids. When a steroid hormone contacts a cell, it is released from its carrier protein. It passes through the plasma membrane of the target cell and then binds to internal receptors in the nucleus or cytosol. Steroid hormones include aldosterone, cortisol, and the sex hormones. Some steroid hormones have very similar structures but produce very different effects. For example, testosterone and estradiol, two major sex hormones that are responsible for the development of male and female characteristics, respectively, differ only in the presence or absence of a single methyl group.

steroid hormone a hormone composed of cholesterol that is not very water soluble; usually passes through the cell membrane and acts on receptors inside the cell

Hormone Mechanisms

Many hormones are secreted in an inactive or less active form called prohormones. Prohormones are converted by the target cells or by enzymes in the blood or other tissues to the active form. Protein hormones are commonly synthesized as prohormones, which are then converted to the active form in the source cell. In some cases, further conversion occurs once the hormone has been secreted. For example, angiotensin is a hormone that regulates blood pressure in humans. It is secreted by the liver as angiotensinogen. An enzyme cleaves an inactive form of angiotensin from angiotensinogen. When this inactive form is converted to the active hormone by the angiotensin-converting enzyme (ACE), there is an increase in blood pressure. ACE inhibitors are often prescribed to control high blood pressure.

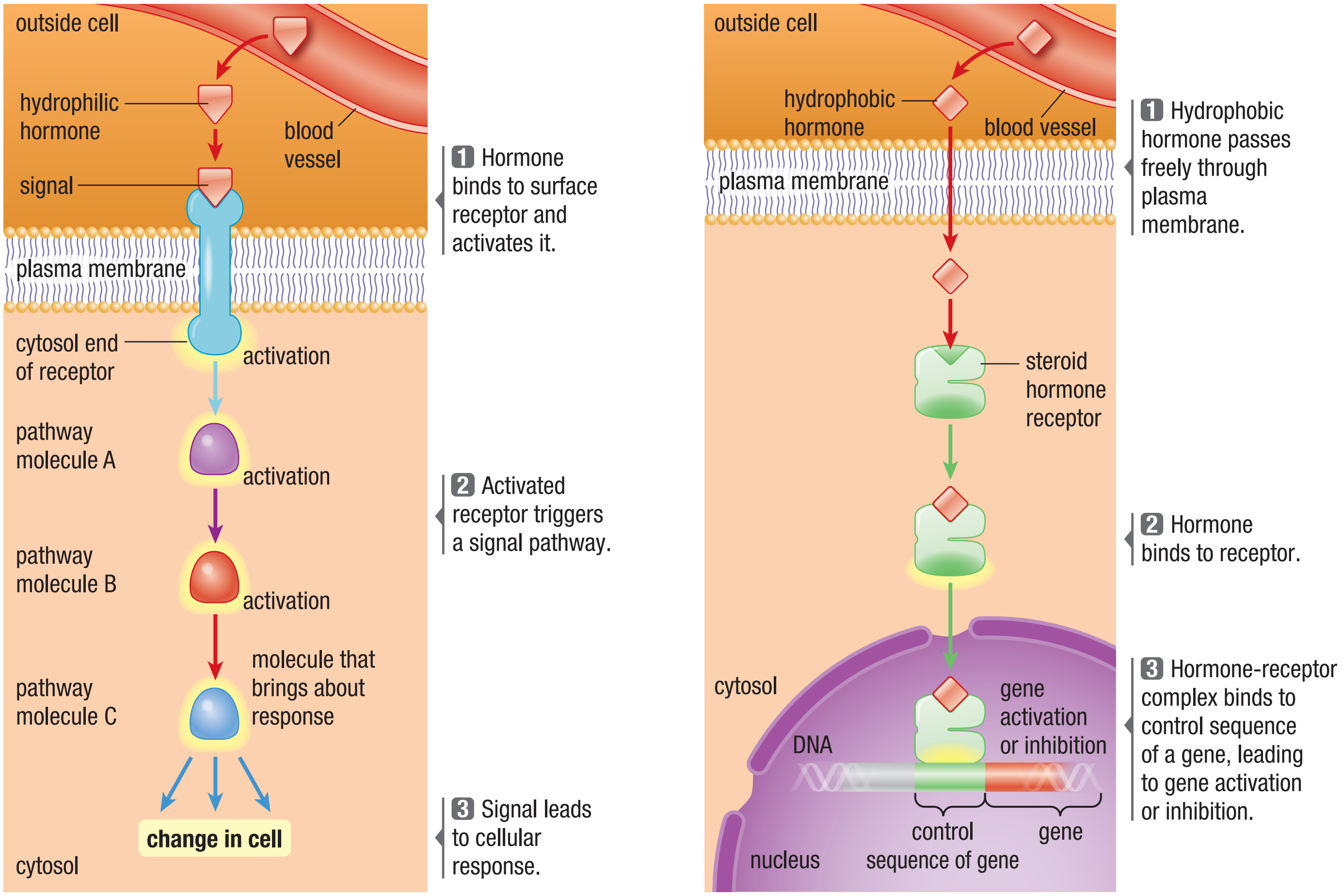
Hormones are usually secreted in relatively small amounts, but a process of amplification magnifies their effects. Once a receptor cell activates a few proteins, these proteins activate other proteins, each of which activates other proteins, and so on. This chain reaction amplifies the effect of the small amount of hormone initially received.

Pathways for Water-Soluble Hormones

Hormones use two main mechanisms to control cellular activities. The first mechanism governs water-soluble protein hormones, which cannot easily cross membranes (**Figure 2(a)**, next page). Protein hormones bind to receptor molecules in the cell membrane, causing the receptor molecule to change shape. This activates a signal, which passes into the cell. The signal causes further changes inside the cell, such as the release of enzymes that add phosphate groups to certain proteins, activating or deactivating them. The signal initiated by the hormone may act in the cytosol only, or it may affect the nucleus of the cell, as with many protein hormones such as growth factors.

An example of the surface receptor mechanism is the protein hormone **glucagon**. When glucagon binds to surface receptors on liver cells, it triggers a series of reactions. These reactions lead to the addition of phosphate groups, which activate the enzyme that governs the breakdown of stored glycogen into glucose.

glucagon a hormone produced by alpha cells in the pancreas that raises the blood glucose level by promoting the breakdown of glycogen in the liver



1 Hormone binds to surface receptor and activates it.

2 Activated receptor triggers a signal pathway.

3 Signal leads to cellular response.

1 Hydrophobic hormone passes freely through plasma membrane.

2 Hormone binds to receptor.

3 Hormone-receptor complex binds to control sequence of a gene, leading to gene activation or inhibition.

(a) water-soluble hormones

(b) lipid-soluble hormones

Figure 2 Reaction pathways are (a) in the plasma membrane for water-soluble hormones, and (b) inside the cell for lipid-soluble hormones.

Pathways for Lipid-Soluble Hormones

The second main mechanism involves hormones binding to receptors inside a cell (**Figure 2(b)**). This mechanism is used by most steroid hormones. Steroid hormones are lipid based and therefore lipid soluble, and they pass easily through the plasma membrane. Steroid hormones attach to receptors in the cytosol or nucleus of a cell. The hormone-receptor complex then binds to a control sequence on a specific gene, turning the gene's action on or off. Activation and deactivation of the gene changes the amount of protein that it synthesizes, which changes the cellular activity.

The internal receptor hormone mechanism can be illustrated by the steroid hormone aldosterone. If blood pressure falls below normal levels, aldosterone is secreted by the adrenal glands. The aldosterone travels through cell membranes and attaches to specific receptors found only in certain cells, including cells in the kidneys, sweat glands, and colon. When aldosterone is attached to a receptor, the receptor acts as a transcription factor for a specific gene, leading to the synthesis of proteins that increase sodium reabsorption. The increase in sodium in the blood then increases water retention and thus blood pressure.

Comparison of Water-Soluble and Lipid-Soluble Mechanisms

The two mechanisms used by hormones are not mutually exclusive. A single target cell may have receptors for several hormones and respond differently to each hormone. For example, the liver cells of vertebrates have receptors for the pancreatic hormones insulin and glucagon. Insulin increases the uptake of glucose and its conversion to glycogen, which decreases the blood glucose level. Glucagon stimulates the breakdown of glycogen into glucose, which increases the blood glucose level.

Conversely, particular hormones can interact with different types of receptors in or on a range of target cells. Different responses are then triggered in each target cell because the receptors trigger different signal pathways. As well, the response to a hormone may differ among species. For example, melatonin, a protein hormone derived from tryptophan, is important in regulating daily and annual cycles in most animals. However, it also plays a role in regulating the salt glands of marine birds.

In summary, the mechanisms by which hormones work have four major features:

1. Only the cells that contain surface or internal receptors for the hormones respond to the hormones.
2. Once bound to their receptors, hormones produce a response by turning cellular processes on or off. They do this by altering the proteins that are functioning in or produced by the cell.
3. Hormones are effective in very small concentrations because of the amplification that occurs in both the surface and internal receptor mechanisms.
4. The response to a hormone differs among target organs and among species.

Hormones as Part of Feedback Mechanisms

The secretion of most hormones is regulated by negative feedback mechanisms. In a negative feedback mechanism, a chemical that is affected at the end of the action pathway of a hormone controls the further action of the hormone by inhibiting an earlier chemical reaction. A response in a feedback loop may be the production of a substance or a decrease in the production of a substance. For example, a brain structure called the hypothalamus releases thyroid-releasing hormone (TRH), which initiates a pair of hormone releases by the pituitary and thyroid glands (**Figure 3**). As the concentration of the thyroid hormone in the blood increases, it inhibits an earlier step in the pathway, the secretion of thyroid-stimulating hormone (TSH) by the pituitary gland.

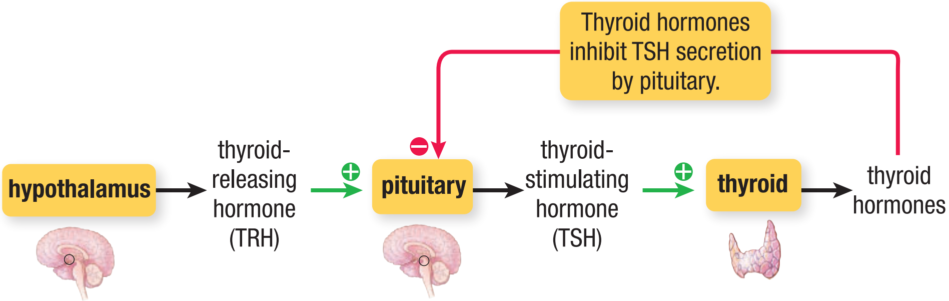

Thyroid hormones inhibit TSH secretion by pituitary.
hypothalamus
thyroid-releasing hormone (TRH)
+
−
pituitary
thyroid-stimulating hormone (TSH)
+
thyroid
thyroid hormones

Figure 3 A simple negative feedback loop regulates the secretion of hormones.

Regulation of Body Processes by Hormones

Some glands produce multiple hormones, and many body processes are affected by more than one hormone at a time. The blood concentrations of glucose, fatty acids, and ions (such as Ca^{2+}, K^{+}, and Na^{+}) are regulated by the coordinated activities of several hormones, which are secreted by different glands. Similarly, body processes such as oxidative metabolism, digestion, growth, sexual development, and reactions to stress are all controlled by multiple hormones.

In many of these systems, negative feedback loops adjust the level of secretion of hormones that act in opposing ways. This creates a balance in their effects that maintains homeostasis in the body. Consider the regulation of fuel molecules, such as glucose, fatty acids, and amino acids, in the blood. In Canada, many people eat three meals a day. Between meals, five separate hormone systems, involving the digestive tract, pancreas, nervous system, and pituitary and adrenal glands, all act together in a coordinated fashion to keep the body's fuel levels in balance.

10.1 Review

Summary

- Most hormones are chemicals secreted by the cells of the endocrine system that control the activities of cells elsewhere in the body.
- Only target cells that have the correct receptor proteins respond to the presence of a specific hormone. Once a receptor protein is bound to a hormone, it signals other proteins inside the cell to turn certain cellular processes on or off.
- Most hormones are either protein hormones or steroid hormones. Protein hormones are water soluble and tend to bind to cell membrane receptors. Steroid hormones are lipids and not as water soluble, but they pass easily through the plasma membrane and tend to attach to receptors inside the cell.
- Hormones can function at low concentrations because their effects can be amplified.
- Many hormones are controlled by negative feedback mechanisms in which the increasing concentration of a chemical turns off further production of a hormone.
- The glands of the endocrine system and their hormones work together to control other body systems and maintain homeostasis.

Questions

1. What is a hormone? K/U
2. Name and describe the two most common types of hormones, classified according to their molecular structure. K/U
3. What are the two main mechanisms that hormones use to produce their effects in target cells? K/U
4. If a particular hormone, such as the hormone that stimulates the development of facial hair, is released throughout the bloodstream, why does it not affect all the cells in the same way? K/U T/I
5. Use a graphic organizer to compare and contrast the endocrine system's methods of controlling and regulating processes in the body with the nervous system's methods. K/U C
6. Testosterone is a hormone derived from cholesterol. Explain how you would expect testosterone to perform its intended action in a cell. T/I
7. Research a hormone whose path was not explained in this section, such as cholecystokinin (CCK), insulin, progesterone, or estrogen. Create a flow chart to explain its pathway. T/I C
8. Osteoporosis is a loss of bone tissue usually associated with aging. Research the hormone calcitonin and its use as a therapy and preventive agent for osteoporosis. Summarize your findings in a report. You are free to choose the format for your report. For example, you could choose to do a written report, an oral presentation, or a slide show. T/I C A
9. Why does the imbalance of a particular hormone affect the entire body and cause so many different symptoms? K/U
10. Steroid hormones bind to receptors inside cells. Why can steroid hormones diffuse into a cell while protein hormones cannot? K/U
11. Use a t-chart to contrast the ways in which steroid and protein hormones
    (a) interact with cell membranes
    (b) get messages into cells
    (c) cause chemical reactions
    (d) make products K/U C
12. How are the target cell's activities changed if a gland produces too much of a particular hormone? Support your answer with an example. K/U

WEB LINK

The Endocrine Glands

10.2

When you hear the word "hormone," what do you think of? Many people think first of sex hormones, such as estrogen and testosterone, but hormones are not limited to sex hormones. Your body contains dozens of different hormones, each tailored to a specific task or sometimes more than one task. Hormones help to make you hungry, and they make you tired when it gets dark.

Hormones, which are produced by the endocrine system, are like a chemical management system for the body. The endocrine system is a system of glands located in various parts of the body. These glands produce hormones and secrete them into the bloodstream, which carries them throughout the body. **Figure 1** shows some of the major endocrine glands in humans. Many other important hormones are secreted by other organs, such as the heart, liver, kidneys, and intestines, and have different primary functions.

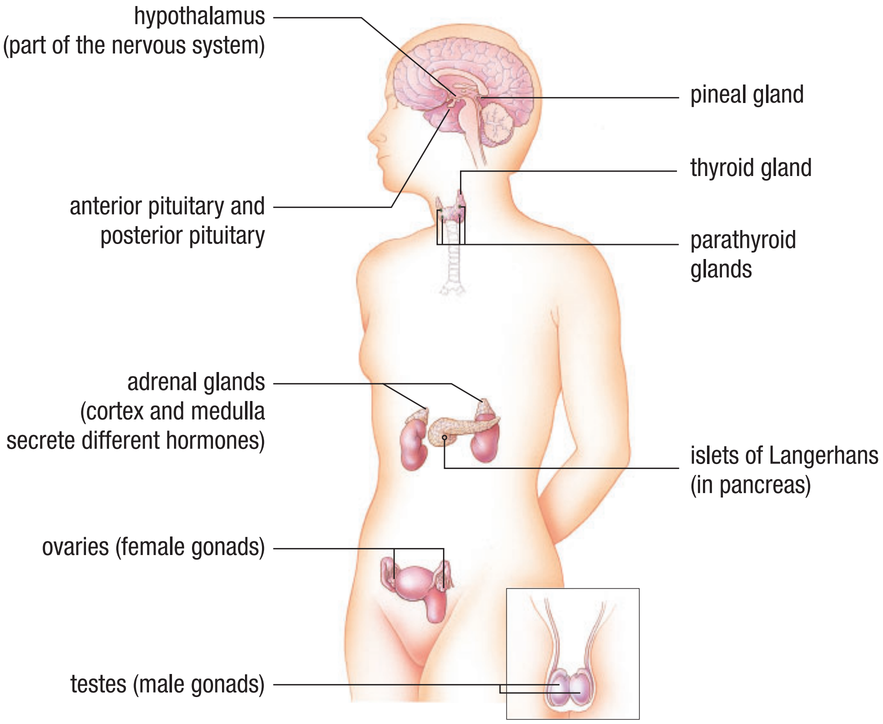


Figure 1 The major endocrine glands and cells in humans

The Vertebrate Endocrine System

In this section, you will consider the hypothalamus and pineal glands, which lie within the brain, and the pituitary gland, which lies just below the brain. You will also consider the thyroid and parathyroid glands in the throat and the adrenal glands on the tops of the kidneys.

Hypothalamus and Pituitary Gland

The **hypothalamus** is unlike other endocrine glands. It is a region of the brain and thus part of the nervous system. The nervous system is a system of specialized cells and fibres that transmit nerve impulses between different parts of the body. Neurons (nerve cells) in the hypothalamus produce a special type of hormone, called **neurohormones**. The neurohormones travel along the length of the nerve cells, diffuse into the bloodstream, and then travel through the blood into the pituitary gland.

hypothalamus the region of the brain that releases hormones to control the pituitary gland, which, in turn, controls other endocrine glands

neurohormone a hormone produced by neurons, such as in the hypothalamus, that controls the production of other hormones in the pituitary gland

The hypothalamus itself is controlled by input from other parts of the nervous system. Some neurons connect directly to the hypothalamus from sensory receptors that monitor the blood for changes in body chemistry or temperature. Input to the hypothalamus also comes from numerous connections from control centres elsewhere in the brain. Negative feedback systems help to control how the hypothalamus releases its hormones.

pituitary gland a two-lobed gland within the cranial cavity that produces hormones that control the other endocrine glands

The **pituitary gland** is located within the cranium, just below the brain. It has two major lobes: the anterior lobe and the posterior lobe. The neurohormones travel through a portal vein that connects capillaries inside the hypothalamus with the capillaries inside the anterior pituitary gland. The portal vein provides a critical link between the nervous system and the endocrine system, because most of the blood that enters the anterior pituitary gland must first pass through the hypothalamus. There are two types of neurohormones produced by the hypothalamus: releasing hormones and inhibiting hormones. These hormones either stimulate or inhibit the release of specific hormones that are created in the anterior pituitary gland. The hormones secreted by the endocrine cells inside the anterior pituitary gland are then released into the bloodstream to reach their target tissues, where they control many other endocrine glands and some bodily processes directly. The hypothalamic and pituitary hormones are summarized in **Table 1**.

Table 1 Hypothalamic and Pituitary Hormones

Endocrine gland	Hormone produced	Target tissue	Function
hypothalamus	releasing and inhibiting hormones, e.g., growth hormone–releasing hormone (GHRH) or growth hormone–inhibiting hormone (somatostatin)	anterior pituitary	regulates the secretion of anterior pituitary hormones
anterior pituitary	prolactin (PRL)	mammary glands	stimulates breast development and milk production
	growth hormone (GH)	bone, soft tissue	stimulates the growth of bones and soft tissues; helps to control the metabolism of glucose and other fuel molecules
	thyroid-stimulating hormone (TSH)	thyroid gland	stimulates the secretion of thyroid hormones and the growth of the thyroid gland
	adrenocorticotropic hormone (ACTH)	adrenal cortex	stimulates the secretion of glucocorticoids by the adrenal cortex
	follicle-stimulating hormone (FSH)	ovaries in females, testes in males	stimulates egg growth and development and the secretion of sex hormones in females; stimulates sperm production in males
	luteinizing hormone (LH)	ovaries in females, testes in males	regulates ovulation in females and the secretion of sex hormones in males
	melanocyte-stimulating hormone (MSH)	melanocytes in the skin of some vertebrates	promotes darkening of the skin
	endorphins	pain pathways in the nervous system	inhibit the perception of pain
posterior pituitary	antidiuretic hormone (ADH)	kidneys	increases blood volume and pressure by increasing water reabsorption in the kidneys
	oxytocin	uterus, mammary glands	promotes uterine contractions; stimulates milk release from the breasts

The pituitary gland is sometimes referred to as the "master gland" because it produces hormones that control most of the other endocrine glands (**Figure 2**). The anterior pituitary secretes several major hormones into the bloodstream, some of which drive hormone secretion in other glands. The posterior lobe of the pituitary gland stores and releases two important hormones, one of which helps to control blood pressure.

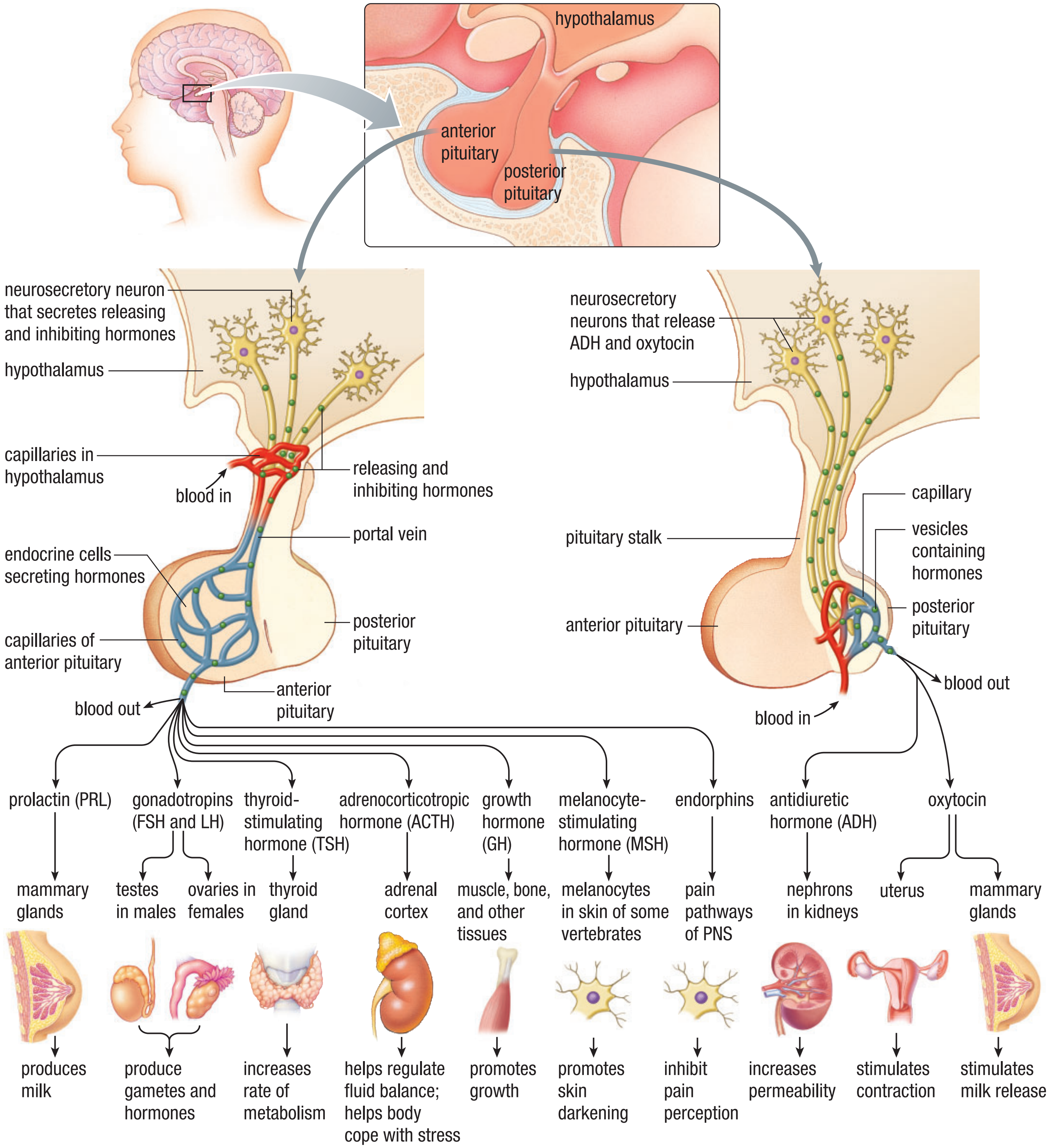

hypothalamus
anterior pituitary
posterior pituitary
neurosecretory neuron that secretes releasing and inhibiting hormones
hypothalamus
capillaries in hypothalamus
blood in
releasing and inhibiting hormones
portal vein
endocrine cells secreting hormones
posterior pituitary
capillaries of anterior pituitary
anterior pituitary
blood out
neurosecretory neurons that release ADH and oxytocin
hypothalamus
capillary
pituitary stalk
vesicles containing hormones
posterior pituitary
anterior pituitary
blood out
blood in
prolactin (PRL)
gonadotropins (FSH and LH)
thyroid-stimulating hormone (TSH)
adrenocorticotropic hormone (ACTH)
growth hormone (GH)
melanocyte-stimulating hormone (MSH)
endorphins
antidiuretic hormone (ADH)
oxytocin
mammary glands
testes in males
ovaries in females
thyroid gland
adrenal cortex
muscle, bone, and other tissues
melanocytes in skin of some vertebrates
pain pathways of PNS
nephrons in kidneys
uterus
mammary glands
produces milk
produce gametes and hormones
increases rate of metabolism
helps regulate fluid balance; helps body cope with stress
promotes growth
promotes skin darkening
inhibit pain perception
increases permeability
stimulates contraction
stimulates milk release

Figure 2 The hypothalamus and the pituitary gland link the endocrine system and the nervous system. Neurohormones produced by the hypothalamus control the anterior and posterior pituitary hormones, which control other endocrine glands.

ANTERIOR PITUITARY GLAND

The endocrine system is largely controlled by the anterior pituitary hormones, which, in turn, are controlled by the releasing or inhibiting hormones that come from the hypothalamus. The anterior pituitary secretes six major hormones into the bloodstream: prolactin, growth hormone, thyroid-stimulating hormone, adrenocorticotropic hormone, follicle-stimulating hormone, and luteinizing hormone (Figure 2).

Prolactin (PRL) influences reproductive activities and parental care in vertebrates. In mammals, PRL stimulates the development of the secretory cells of the mammary glands during late pregnancy, and milk synthesis after birth. Stimulation of the mammary glands and the nipples, which occurs during suckling, leads to the release of PRL. In all vertebrates, PRL has a role in promoting both maternal and paternal behaviour. PRL also occurs in non-mammalian vertebrates, where it has a variety of functions. In fish, for example, it is one of the hormones that controls water balance.

Growth hormone (GH) stimulates cell division, protein synthesis, and bone growth in children and adolescents, thereby causing body growth. GH also stimulates protein synthesis and cell division in adults. To carry out these functions, GH binds to muscle and other target tissues, causing them to release insulin-like growth factor (IGF), a protein hormone that directly stimulates the growth processes. GH also directly controls a number of major metabolic processes in mammals of all ages, including the conversion of glycogen to glucose and fats to fatty acids as a means of regulating their levels in the blood. As well, GH stimulates body cells to take up fatty acids and amino acids and limits the rate at which muscle cells can take up glucose. These actions help to maintain the availability of glucose and fatty acids to tissues and organs between meals, which is particularly important for the brain. In humans, deficiencies in GH secretion during childhood produce pituitary dwarfs, who remain small in stature (**Figure 3(a)**). Overproduction of GH during childhood or adolescence, often due to a tumour of the anterior pituitary, produces pituitary giants, who may grow up to 2.7 m in height (**Figure 3(b)**).

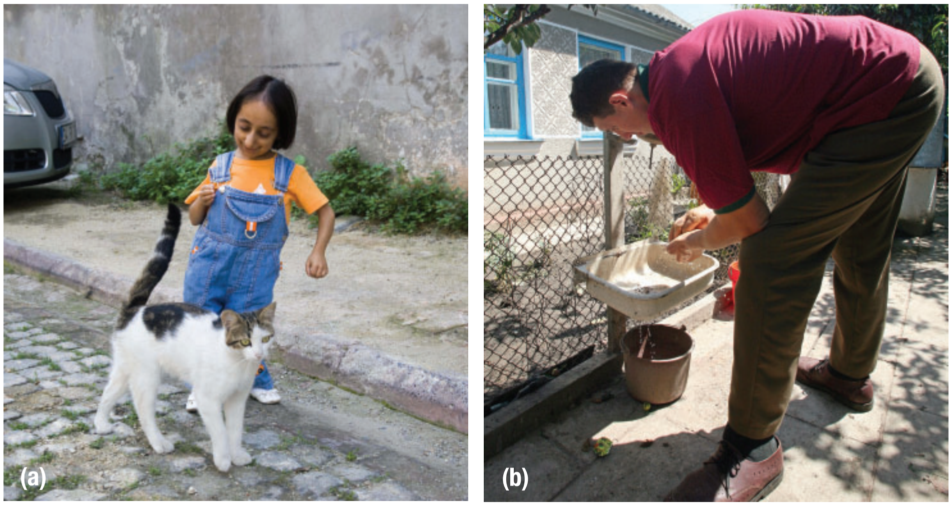


Figure 3 (a) A pituitary dwarf and (b) a pituitary giant

Many of the other hormones secreted by the anterior pituitary gland control endocrine glands elsewhere in the body. These hormones are referred to as tropic hormones. Thyroid-stimulating hormone (TSH) stimulates the thyroid gland to grow in size and secrete thyroid hormones. Adrenocorticotropic hormone (ACTH) triggers hormone secretion by cells in the adrenal cortex. Follicle-stimulating hormone (FSH) affects egg development in females and sperm production in males. As well, it stimulates the secretion of sex hormones in female mammals. Luteinizing hormone (LH) regulates part of the menstrual cycle in human females and the secretion of sex hormones in males. FSH and LH are grouped together as gonadotropins because they regulate the activities of the gonads (ovaries and testes). The roles of the gonadotropins and sex hormones in the reproductive cycle are described in Section 10.7.

Melanocyte-stimulating hormone (MSH) and endorphins are also secreted by the anterior pituitary gland. MSH is named because of its effect on melanocytes, skin cells that contain the black pigment melanin. An increase in MSH secretion produces a darkening of the skin of fish, amphibians, and reptiles. The darkening is caused by a dispersal of melanin in melanocytes so that it covers a greater area. In humans, an increase in MSH secretion also causes skin darkening, although the effect is not as obvious. MSH secretion increases in pregnant women. Combined with the effects of increased estrogens, MSH results in increased skin pigmentation. The effects are reversed after the birth of the baby.

Endorphins—protein hormones produced by the hypothalamus and the pituitary gland—are released by the intermediate lobe of the pituitary gland. In humans, the intermediate lobe is not well developed, comprising only a thin layer of cells between the anterior and posterior lobes. In the human nervous system, endorphins act as neurotransmitters in pathways that control pain, thereby inhibiting the perception of pain. Hence, endorphins are often called "natural painkillers."

POSTERIOR PITUITARY GLAND

The posterior lobe of the pituitary gland stores and releases two important hormones, antidiuretic hormone and oxytocin, into the bloodstream (Figure 2). These hormones are produced in the cells of the hypothalamus. They are transferred to the posterior pituitary gland along nerve cells that reach from the hypothalamus into the posterior pituitary. The posterior pituitary gland stores the hormones and releases them into the bloodstream when the appropriate nerves from the hypothalamus are stimulated.

Antidiuretic hormone (ADH) stimulates the kidney cells to absorb more water from the urine, which increases the volume of the blood. ADH is released when sensory receptor cells of the hypothalamus detect an increase in the blood's Na^+ concentration after a salty meal or when the body is dehydrated. Ethanol and caffeine inhibit ADH secretion, explaining, in part, why alcoholic drinks and coffee increase the volume of urine excreted. Nicotine and emotional stress, in contrast, stimulate ADH secretion and water retention. After severe stress is relieved, the return to normal ADH secretion often makes a trip to the bathroom among our most pressing needs. The hypothalamus also releases a flood of ADH when an injury results in heavy blood loss or another event triggers a severe drop in blood pressure. ADH helps maintain blood pressure by reducing water loss and causing blood vessels in some tissues to constrict.

ADH enables the kidneys to maintain a homeostatic balance of extracellular fluid in the body. Most (approximately 85 %) of the water filtered into the nephron is reabsorbed in the proximal convoluted tubule. The remainder is absorbed in the distal convoluted tubule, but only if ADH is present. ADH causes the upper part of the distal convoluted tubule to become permeable to water. The high concentration of NaCl in the interstitial fluid causes water to move, by osmosis, out of the upper part of the distal tubule and the collecting duct into the interstitial fluid. It is the control of this volume of water (15 %) in the kidneys that balances the concentrations of the body fluids.

Hormones similar to those of ADH are also secreted in fish, amphibians, reptiles, and birds. In amphibians, these ADH-like hormones increase the amount of water that enters the body through the skin and from the urinary bladder.

Oxytocin is the second important hormone stored and released by the posterior lobe of the pituitary gland. Oxytocin stimulates the release of milk from the mammary glands of a nursing mother. The stimulation of the nipples in suckling sends neuronal signals to the hypothalamus and leads to the release of oxytocin. The released oxytocin stimulates more oxytocin secretion by a positive feedback mechanism. Oxytocin causes the smooth muscle cells surrounding the mammary glands to contract, forcibly expelling the milk through the nipples. The entire cycle, from the onset of suckling to milk ejection, takes less than a minute in mammals. Oxytocin also plays a key role in childbirth by stimulating the contraction of the muscles of the uterus.

In males, oxytocin is also secreted into the seminal fluid by the testes. When the seminal fluid is ejaculated into the vagina during sexual intercourse, oxytocin stimulates contractions of the uterus, which aid the movement of sperm through the female reproductive tract.

Thyroid and Parathyroid Hormones

thyroid gland an endocrine gland located in the throat that is regulated by the hypothalamus-pituitary system

The **thyroid gland** is located in the front of the throat in humans and is shaped like a bow tie. It secretes the same hormones in all vertebrates. The thyroid hormones have an extraordinarily wide range of effects. The primary thyroid hormone, thyroxine, is known as T_4 because it contains four iodine atoms. A supply of iodine in the diet is necessary to produce all of these hormones. Normally, the concentrations of thyroid hormones are kept at finely balanced levels in the blood by negative feedback loops. **Table 2** lists the thyroid and parathyroid hormones and their functions in the body.

Table 2 Thyroid and Parathyroid Hormones

Endocrine gland	Hormone produced	Target tissue	Function
thyroid	calcitonin	bones	lowers the calcium concentration in the blood
	thyroxine and triiodothyronine	most cells	increases the metabolic rate; essential for normal body growth
parathyroid	parathyroid hormone (PTH)	bones, kidneys, and intestines	raises the calcium concentration in the blood; stimulates vitamin D activation

When there is not enough iodine in the body to produce thyroxine, the negative feedback loop fails and the thyroid is continually stimulated by TSH from the pituitary gland. The overstimulated thyroid swells and results in a condition called a goiter, which can result in a noticeable swelling on the neck (**Figure 4**). To ensure that people get enough iodine in their diet to produce thyroxine and prevent goiter, iodine is added to table salt in many places in the world, including Canada.

The thyroid hormone T_4 is not a steroid hormone, but it is lipid soluble and can pass through the cell membrane. Once inside the cell, T_4 loses an iodine atom and is converted into T_3. T_3 enters the nucleus and combines with nuclear receptors. There, it alters gene expression, bringing about many of its effects.

Thyroid hormones are vital to growth, development, maturation, and metabolism in all vertebrates. They interact with growth hormone for their effects on growth and development. Thyroid hormones also increase the sensitivity of many body cells to the effects of epinephrine and norepinephrine—hormones released by the adrenal medulla as part of the fight-or-flight response. In amphibians, rising concentrations of thyroid hormones trigger metamorphosis or a change in body form from tadpole to adult (**Figure 5**). Thyroid hormones also contribute to seasonal moulting, leading to changes in the plumage of birds and the coat colour of mammals.

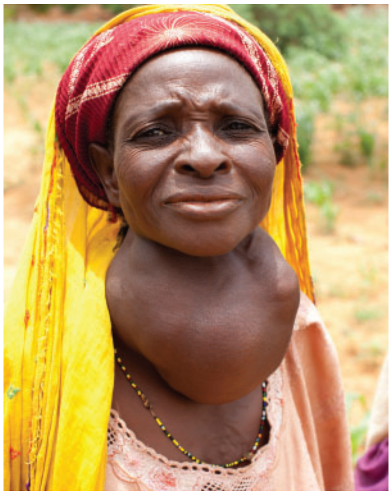


Figure 4 The very swollen area on the neck is a goiter, an enormously enlarged thyroid gland. Goiters are more common in parts of the world without modern medical care and without a natural supply of iodine in the diet.

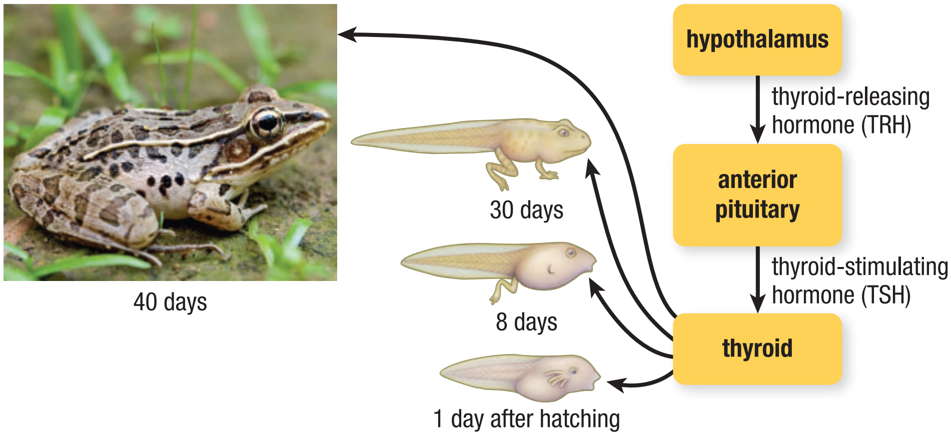


Figure 5 Metamorphosis of a tadpole into an adult frog is controlled by the thyroid hormones.

In mammals, the thyroid also has specialized cells that secrete calcitonin, a protein hormone. Calcitonin was originally discovered in fish by Dr. Harold Copp, a professor at the University of British Columbia. This hormone lowers the level of Ca^{2+} in the blood by inhibiting the ongoing release of calcium from bones. Calcitonin secretion is stimulated when the Ca^{2+} level in the blood rises above the normal range. It is inhibited when the Ca^{2+} level falls below the normal range. Although the specialized cells of the thyroid are the principal source, calcitonin is also synthesized in the lungs and intestines.

The parathyroid glands are found only in amphibians, reptiles, birds, and mammals. Mammals have four parathyroid glands, two on each side of the posterior surface of the thyroid gland. Each parathyroid is a spherical structure about the size of a pea. The single hormone they produce, called **parathyroid hormone** (PTH), is secreted in response to a fall in the Ca^{2+} level in the blood (**Figure 6**). The PTH pathway is a negative feedback loop. PTH stimulates bone cells to dissolve the mineral matter of bone tissues, releasing both calcium and phosphate ions into the blood. The released Ca^{2+} is available for enzyme activation, conduction of nerve signals across synapses, muscle contraction, blood clotting, and other uses.

parathyroid hormone a hormone secreted by the parathyroid glands that controls calcium and phosphate levels in the blood

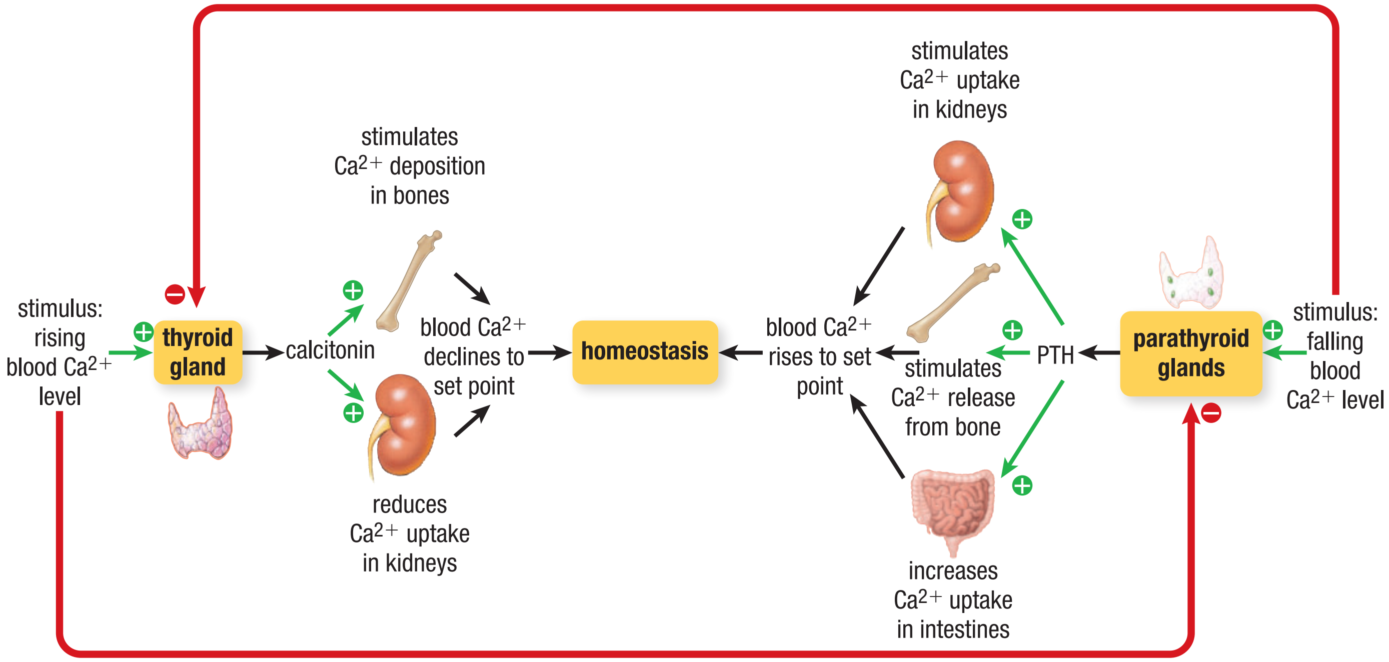

stimulus: rising blood Ca2+ level
thyroid gland
calcitonin
stimulates Ca2+ deposition in bones
reduces Ca2+ uptake in kidneys
blood Ca2+ declines to set point
homeostasis
blood Ca2+ rises to set point
stimulates Ca2+ uptake in kidneys
stimulates Ca2+ release from bone
increases Ca2+ uptake in intestines
PTH
parathyroid glands
stimulus: falling blood Ca2+ level

Figure 6 The negative feedback control of parathyroid hormone (PTH) and calcitonin by the Ca^{2+} level in the blood

PTH also stimulates enzymes in the kidneys to convert vitamin D, a steroid-like molecule, into calcitriol, its fully active form in the body. The activated vitamin D increases the absorption of Ca^{2+} and phosphates from ingested food by promoting the synthesis of a calcium-binding protein in the intestines. It also increases the release of Ca^{2+} from bones in response to PTH.

PTH underproduction causes the Ca^{2+} concentration in the blood to fall steadily, disturbing nerve and muscle function. As a result, the muscles twitch and contract uncontrollably, and convulsions and cramps occur. Without treatment, the condition is usually fatal because the severe muscular contractions interfere with breathing. Overproduction of PTH results in the loss of so much calcium from the bones that they become thin and fragile. This condition is known as osteoporosis. At the same time, the elevated Ca^{2+} concentration in the blood causes calcium deposits to form in soft tissues, especially in the lungs, arteries, and kidneys (where the deposits form kidney stones).

Although fish do not have a parathyroid gland, they produce PTH and have PTH receptors. However, the origin of the hormone and its precise function remain uncertain.

Adrenal Hormones

The adrenal glands of mammals (from *ad* meaning "next to" or "near" and *renes* meaning "kidneys") have two distinct regions. The central region, the adrenal medulla, contains highly modified neurosecretory neurons. The tissue surrounding the adrenal medulla, the adrenal cortex, contains non-neural endocrine cells. The two regions secrete hormones with entirely different functions.

The adrenal medulla secretes two adrenal hormones, epinephrine and norepinephrine, which are chemicals that can act as hormones or neurotransmitters (chemicals that transmit nerve signals). They bind to receptors in the plasma membrane of their target cells. Norepinephrine is also released as a neurotransmitter by some neurons of the nervous system. The adrenal cortex secretes several hormones, including aldosterone and cortisol. Aldosterone, the main hormone of the group of mineralocorticoids, is involved in osmoregulation and control of blood pressure. Cortisol is the main hormone of a group of glucocorticoid hormones that help to regulate blood glucose levels and promote the breakdown of fats and proteins as alternative fuels when the glucose supply is low.

Epinephrine and norepinephrine are secreted when the body encounters stresses such as emotional excitement, danger (fight-or-flight situations), anger, fear, infection, injury, and even anxiety about midterm and final exams. Epinephrine, in particular, prepares the body for handling stress or physical activity. It causes the heart rate to increase and glycogen and fats to break down, releasing glucose and fatty acids into the blood as fuel molecules. In the heart, skeletal muscles, and lungs, the blood vessels dilate to increase blood flow. Elsewhere in the body, the blood vessels constrict. This raises blood pressure, reduces blood flow to the intestines and kidneys, and inhibits smooth muscle contractions, thus reducing water loss and slowing down the digestive system. At the same time, airways in the lungs dilate, helping to increase the flow of air. The effects of norepinephrine on heart rate, blood pressure, and blood flow to the heart muscle are similar to those of epinephrine.

The effects of epinephrine are what make it a life-saving drug for someone who is experiencing a severe allergic reaction called anaphylaxis. A person who has an extreme allergy—to nuts, insect venom, or any of a large group of allergens—can go into shock and die from an anaphylactic reaction. Epinephrine is the drug of choice to counter anaphylaxis. Its effects are immediate, opening airways and raising blood pressure. People with severe allergies often carry a pen-shaped epinephrine auto-injector that they can use in an emergency.

Pineal Gland

pineal gland an endocrine gland located in or on the brain of vertebrates that secretes the hormone melatonin to regulate biological rhythms

The **pineal gland** regulates several biological rhythms. It is found at different locations in the brain of vertebrates. In mammals, it is near the centre of the brain. In birds and reptiles, it is on the surface of the brain, just under the skull, and is directly sensitive to light. Some of the earliest vertebrates had a light-sensitive organ at the top of the head (called a third eye), and some lizards retain an eyelike structure in this location. In most vertebrates, the third eye became modified into a pineal gland, which may retain some degree of photosensitivity. In mammals, it is too deeply buried in the brain to be affected directly by light. Nonetheless, specialized photoreceptors in the eyes make connections to the pineal gland.

The pineal gland secretes the neurohormone melatonin, which helps to maintain daily biorhythms. The secretion of melatonin is regulated by an inhibitory pathway. When light hits the eyes, it generates signals that inhibit melatonin secretion. As a result, melatonin is secreted most actively during periods of darkness. Melatonin targets a part of the hypothalamus that coordinates body activity to a daily cycle. The nightly release of melatonin may help to synchronize the biological clock with daily cycles of light and darkness. The physical and mental discomfort associated with jet lag may reflect the time that is required for melatonin secretion to reset a traveller's daily biological clock to match the period of daylight in a new time zone. Melatonin is found in organisms throughout the animal kingdom, as well as in many plants and fungi. In invertebrates, it helps control diurnal (daily) rhythms.

Table 3 lists the hormones of the adrenal and pineal glands.

Table 3 Adrenal and Other Hormones

Endocrine gland	Hormone produced	Target tissue	Function
adrenal medulla	epinephrine and norepinephrine throughout the body	receptor sites throughout the body	contribute to the body's responses to stress
adrenal cortex	aldosterone (mineralocorticoid)	kidney tubules	helps to control the salt–water balance in the body by increasing Na^+ reabsorption and K^+ excretion in the kidneys
	cortisol (glucocorticoid)	most body cells, particularly muscle, liver, and adipose cells	increases the blood glucose level by promoting breakdown of proteins and fats
pineal gland	melatonin	brain, anterior pituitary gland, reproductive organs, immune system, and possibly others	helps to synchronize the body's biological clock with day length; may inhibit gonadotropins and the initiation of puberty

Overview of the Invertebrate Endocrine System

Among the best-known invertebrate hormonal systems is the system that governs the growth and development of insects (**Figure 7**). As insects grow, they undergo a series of moults. A new exoskeleton—the hard body covering—is laid down beneath the old exoskeleton, which is then shed. The signal to begin the process is provided by a steroid hormone called ecdysone. The glands that secrete ecdysone respond to a neurohormone produced in the brain.

Juvenile hormone controls the metamorphosis of an insect. When it is present, the insect remains larval. If juvenile hormone is absent, the next moult is metamorphic, producing a pupa and then an adult in some insects, or proceeding directly to the adult in insects lacking a pupal stage. The adult of most insects secretes juvenile hormone and stimulates a number of reproductive processes, especially egg development. The secretion of juvenile hormone is controlled by both inhibitory and stimulatory protein hormones from the brain.

Hormones that control moulting have also been detected in crustaceans, such as lobsters, crabs, and crayfish. During the period between moults, a moult-inhibiting hormone inhibits ecdysone secretion. Therefore, the first step in the moulting process involves inhibiting the secretion of this moult-inhibiting hormone. Ecdysone secretion increases, and the processes leading to the replacement of the exoskeleton are initiated. As in insects, metamorphosis and reproduction are governed by a hormone that is different from, but structurally related to, juvenile hormone.

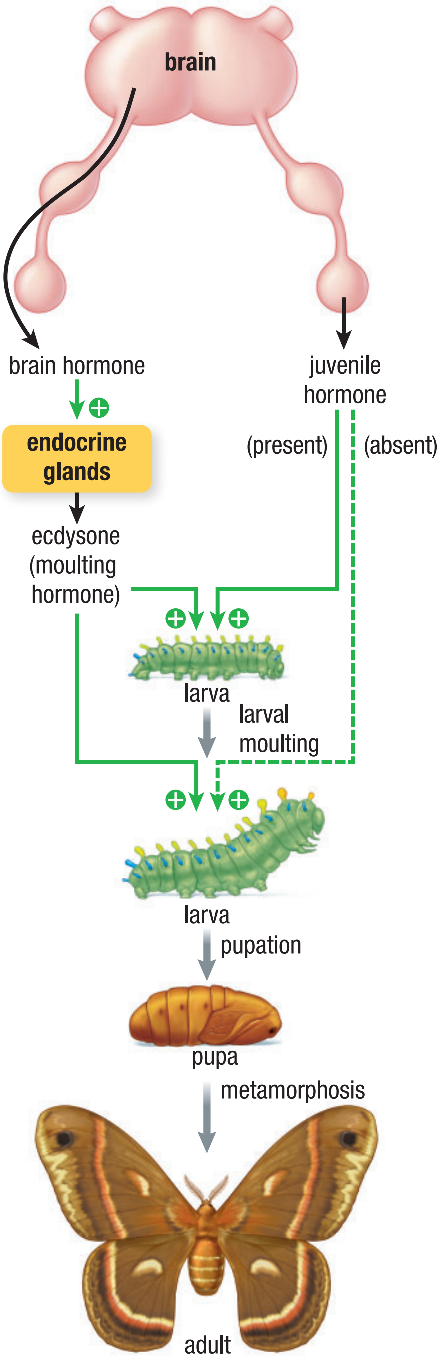


Figure 7 The life cycle of a silkworm moth is controlled by a brain hormone called ecdysone, as well as juvenile hormone.

10.2 Review

Summary

- The endocrine system of glands and the hormones that they produce regulate bodily processes, maintain homeostasis, and control growth, development, and reproduction.
- The hypothalamus and pituitary gland control other endocrine cells and glands throughout the body. The hypothalamus responds to messages from the brain or nerve receptors by releasing hormones. These hormones control the pituitary gland's secretion of other hormones, which regulate the rest of the endocrine system.
- The thyroid gland secretes hormones that control the metabolism of the body and regulate growth and development. The parathyroid glands regulate the concentration of calcium ions in the blood.
- The adrenal glands release epinephrine and norepinephrine, which control the body's response to stress. The adrenal cortex produces glucocorticoid hormones, which help to regulate the blood glucose level.
- The pineal gland helps to regulate biological rhythms by producing the hormone melatonin.
- Many of the hormones found in vertebrates are also found in invertebrates, although their functions may differ. Hormones in invertebrates control metamorphosis, moulting, and reproduction.

Questions

1. Which hormones are primarily responsible for regulating the metabolism of the body? K/U
2. Which hormones help the body respond to stress? K/U
3. How does the function of the posterior pituitary gland differ from the function of the anterior pituitary gland? K/U
4. In both Grade 10 Science and Grade 11 Biology, you learned about the interdependence of body systems. Prepare a brief presentation for Grade 10 or Grade 11 students to help them understand how the endocrine system is linked to and controlled by the nervous system. K/U T/I C
5. Suppose that the thyroid gland had to be removed due to cancer. How would the body be affected, and what treatments do you think would be necessary? T/I
6. What hormones from the anterior pituitary gland are important for reproduction, and what are their functions? K/U
7. Why do alcoholic drinks and coffee increase urination? K/U
8. Why is epinephrine therapeutic for anaphylaxis? Under what conditions might taking epinephrine be dangerous? K/U
9. Which endocrine gland may have been sensitive to light in early vertebrates? How does it respond to light in modern animals? K/U
10. What harmful effect would a complete lack of ecdysone have on a growing invertebrate, such as an insect? T/I
11. How do the releasing hormones of the hypothalamus connect the nervous and endocrine systems? K/U
12. The thyroid gland's production of thyroid hormones (T_3 and T_4) is triggered by thyroid-stimulating hormone (TSH), which is made by the pituitary gland. K/U T/I
    (a) Predict how your body might be affected if the pituitary gland produced too much TSH.
    (b) Predict how it might be affected if the pituitary gland produced too little TSH.
13. In mammals, the pineal gland is located deep in the brain. How can this gland be light-sensitive? K/U

Regulating Blood Sugar

10.3

Like most processes of the endocrine system, the regulation of our blood sugar level normally occurs automatically—we do not have to think about it. The only time most of us may think about our blood sugar level is when we are feeling very hungry or after we have eaten something very sweet. Imagine having to monitor and control your blood sugar level. The body's ability to regulate its own internal processes and maintain homeostasis is one of the amazing things about the endocrine system. Since all of the body's cells use glucose as fuel, the regulation of the blood glucose level is crucial to maintaining homeostasis.

Sometimes, the endocrine system can have problems. If homeostasis is not maintained, some of the bodily processes may become imbalanced or may not be properly regulated. Many people have a problem with their blood glucose monitoring system, a condition called diabetes mellitus (Section 8.1). In 2000, there were an estimated 2 million diagnosed cases of diabetes in Canada. More than 60 000 new cases are diagnosed each year. People who have diabetes, called diabetics, have a blood glucose level that may fluctuate abnormally, changing their metabolism and leading to some serious health risks and long-term problems. Diabetics must be aware of their blood glucose level at all times. Thankfully, scientific research has led to modern technologies that can help diabetics. Electronic monitors allow diabetics to test their blood glucose level throughout the day, and modern syringes, pens, and pumps allow them to administer insulin to control their blood glucose level (**Figure 1**). Finding treatments for people with diabetes and other endocrine system failures has been a long-time goal and major success of modern medical research. Imagine how life would have been different for Chris Jarvis if these technologies were not available.

Figure 1 People with diabetes may need to inject insulin to control their blood glucose level.

Hormones That Control Blood Sugar

The two main hormones that control blood sugar are produced in the pancreas. The pancreas is a long gland, about the size of a hand, located between the small intestine and the spleen. Most of the pancreas forms an exocrine gland that secretes digestive enzymes into the small intestine, but about 2 % of the cells in the pancreas are specialized endocrine cells that form clusters called the **islets of Langerhans**. Found in all vertebrates, these islets produce the protein hormones insulin and glucagon, which work together to control the blood glucose level. You will read about the discovery of insulin in the early twentieth century by Canadian medical scientist Frederick Banting and his colleagues, including Charles Best, in Section 10.4.

islets of Langerhans endocrine cell clusters inside the pancreas that produce insulin and glucagon

Insulin and glucagon regulate the ability of most tissues in the body to metabolize fuel substances. Insulin is secreted by beta cells in the islets. A rise in the blood glucose level, such as after a meal, triggers the beta cells to release insulin. Insulin lowers the blood glucose level by instructing its target cells to uptake glucose from the blood. Insulin acts mainly on skeletal muscles, liver cells, and adipose tissue (fat). In the liver, insulin inhibits the breakdown of glycogen into glucose, further helping to lower blood glucose levels. Insulin also lowers fatty acid levels by promoting fatty acid uptake and storage in adipose tissue, while inhibiting the breakdown of fats into fatty acids. Similarly, insulin lowers amino acid levels by promoting protein synthesis from amino acids, while inhibiting the breakdown of proteins into amino acids.

The effects of glucagon, secreted by alpha cells in the islets, are opposite to the effects of insulin. Glucagon raises the blood glucose level by stimulating the breakdown of glycogen into glucose in the liver. Glucagon also stimulates the breakdown of fats into fatty acids and of proteins into amino acids. Cells can use amino acids and other non-carbohydrates to synthesize glucose as well. This helps to maintain the blood glucose level during fasting.

Negative feedback mechanisms control the concentration of glucose in the blood and increase or decrease the secretions of both insulin and glucagon in order to maintain glucose homeostasis. The alpha and beta cells of the islets in the pancreas respond directly to the glucose level within their cytosol. When the blood glucose level is high, the beta cells turn up their insulin production while the alpha cells turn down their glucagon production (**Figure 2**). Both of these actions lower the blood glucose level. When the blood glucose level is low, the opposite occurs: alpha cells turn up their glucagon production while beta cells turn down their insulin production, thus raising the blood glucose level.

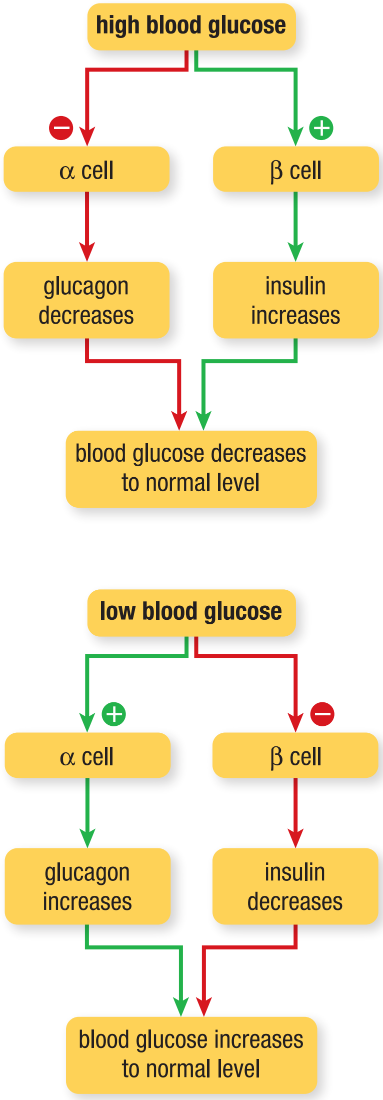


Figure 2 The opposing actions of insulin and glucagon work together through negative feedback mechanisms to maintain the blood glucose level.

The adrenal glands also play a role in controlling blood sugar. The adrenal cortex secretes steroid hormones called glucocorticoids. (As you learned in Section 10.2, the main glucocorticoid is cortisol.) The glucocorticoids help to raise the blood glucose level using three major mechanisms. First, they stimulate the synthesis of glucose from non-carbohydrate sources, such as fats and proteins. Second, they reduce glucose uptake by the body cells, except those in the central nervous system. Third, they promote the breakdown of fats and proteins, releasing fatty acids and amino acids into the blood as alternative fuels when the glucose supply is low. The favouring of glucose uptake in the central nervous system keeps the brain well supplied with glucose between meals and during periods of extended fasting.

The secretion of glucocorticoids is ultimately under the control of the hypothalamus. A low glucose concentration in the blood, or an elevated level of epinephrine secreted by the adrenal medulla in response to stress, is detected in the hypothalamus. This leads to the secretion of adrenocorticotropic hormone (ACTH) by the anterior pituitary. ACTH then promotes the secretion of glucocorticoids by the adrenal cortex.

Despite the body's different mechanisms for maintaining glucose homeostasis, the level of glucose in the blood is not completely constant. It varies throughout the day, largely due to meals and sleep. The graph of the blood glucose level in **Figure 3** shows an overall slow decrease during the night, with spikes bringing the level of glucose up after each meal during the day. Notice that the scale indicating the insulin level is much smaller than the scale used to indicate the glucose level: 1 mmol (the unit used to measure blood glucose) is equal to 1 million pmols (the unit used to measure serum insulin). So, the concentration of insulin in the blood is much lower than the concentration of glucose, but, as this graph shows, it rises and falls with the glucose level.

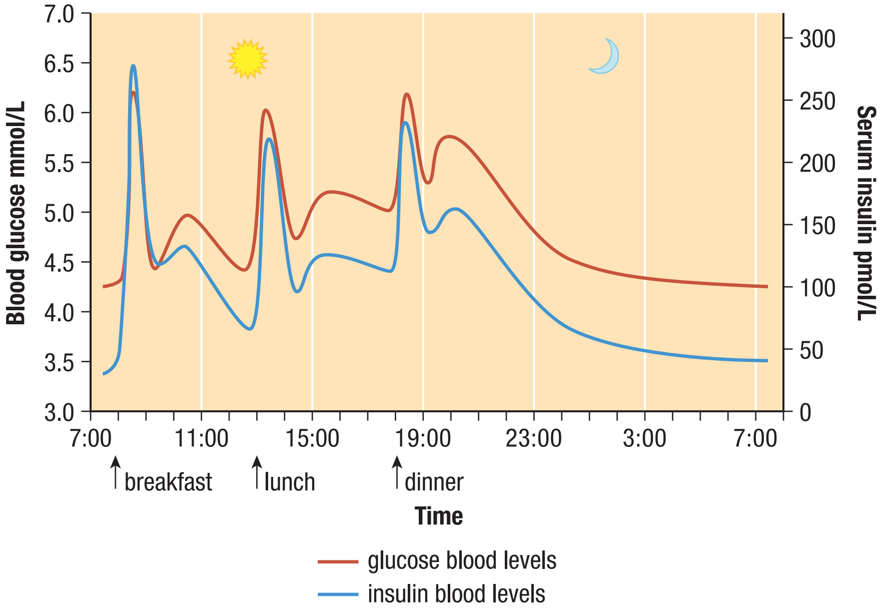


Figure 3 Typical levels of blood glucose and insulin over a 24 h period

A blood glucose level that is too high can cause a condition called hyperglycemia. Symptoms of hyperglycemia may include thirst, frequent urination, sugar in the urine, vision problems, fatigue, and weight loss. A blood glucose level that is too low can cause a condition called hypoglycemia. Symptoms of hypoglycemia may include nervousness, shaking, cold sweats, hunger, headaches, and weakness.

Diabetes

Think about what you have learned about diabetes in previous courses or in your everyday experiences. Perhaps you or someone you know has diabetes. Although little can be done about the cause of diabetes, there are a few factors that can be addressed to reduce the risk of developing diabetes.

Diabetes mellitus, commonly known as diabetes, is a disease characterized by a high blood glucose level caused by problems with insulin production and/or action. Diabetes afflicts about 6 % of the world's population. The three classic diabetes symptoms are frequent urination, increased thirst (and consequently increased fluid intake), and increased appetite. Frequent urination occurs because the ability of the body cells to take up glucose is impaired, leading to an abnormally high glucose concentration in the blood. This results in a high level of glucose in the kidneys, which causes more water to be pulled from the blood by osmosis in the nephrons, which, in turn, leads to excessive amounts of urine. The need to replace the excreted water causes increased thirst. Increased appetite occurs because the body cells cannot get enough energy from glucose, since there is no insulin to help with the glucose uptake. Without insulin, glucose does not enter the body cells very well. Proteins and fats may be broken down as energy sources instead, leading to further deficiencies that increase hunger for these nutrients. Without extra food intake, weight loss will occur. Other symptoms of diabetes can include blurred vision, lethargy, nausea, vomiting, and abdominal pain. If left untreated, diabetes can lead to long-term health problems, including loss of vision, kidney failure, hypertension, and cardiovascular problems.

Diabetes is classified into three different types: type 1, type 2, and gestational diabetes. The reasons for the failure of insulin to regulate the blood sugar are what distinguish these three types.

Type 1 diabetes occurs because the beta cells in the islets of Langerhans in the pancreas do not produce any insulin. This degeneration of beta cells can begin in infancy, so people with type 1 diabetes are usually diagnosed in childhood. Type 1 diabetes is sometimes called juvenile diabetes or insulin-dependent diabetes. Type 1 diabetics must be closely monitored, with frequent blood glucose tests, and treated with the daily administration of insulin, usually by injections or a pump.

Type 2 diabetes occurs from reduced insulin production and/or the inability of insulin to bind to its receptors properly. Type 2 diabetes usually develops in adulthood and is strongly associated with obesity. About 90 % of diabetics have type 2 diabetes. There is a strong genetic link associated with type 2 diabetes—more than 80 % of type 2 diabetics have a family member with type 2 diabetes. Because type 2 diabetics still have the ability to produce insulin, treatment often involves controlling diet and exercise to restore a normal level of insulin production. Since lifestyle factors (such as obesity, a high-calorie diet, and physical inactivity) play a role in developing type 2 diabetes, changing these factors can delay or prevent its onset in some people. Oral drugs may also be given to type 2 diabetics to increase insulin production or to encourage the binding of insulin to its receptors.

A third type of diabetes is called gestational diabetes. It occurs in about 2 to 10 % of pregnant women, due to a high blood glucose level that develops during pregnancy. It is usually a temporary condition, but it can increase the risk that both mother and child may develop diabetes later in life.

Although there is currently no cure for diabetes, there is a significant amount of ongoing medical research into finding a cure and developing better treatments for people who have diabetes (Section 8.1). Most diabetics now have a wide variety of electronic and mechanical devices to help them test their blood sugar level throughout the day and administer their own insulin. The latest external insulin pumps can both monitor the blood glucose level continuously and deliver insulin by a tube through the abdomen. It is certainly not too much of a leap to imagine an entirely internal device that does the same, essentially acting as a mechanical pancreas.

UNIT TASK **BOOKMARK**

Depending on the case study you choose to develop, you may be able to apply what you learned in this section about diabetes to the Unit Task described on page 566.

Mini **Investigation**

Analyzing the Effects of Hormones on the Blood Glucose Level

Skills: Hypothesizing, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK **A2.1**

The graph in **Figure 4** shows the blood glucose levels of two people, John and Ehud, over a 12 h period. John has diabetes; Ehud does not. They ate identical meals and exercised for 1 h at the same times.

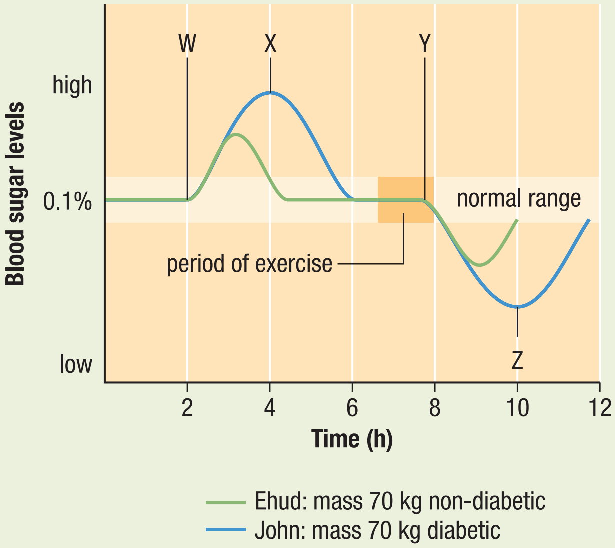


Figure 4 Blood glucose levels for two people, one diabetic and one not, over a 12 h period

1. Analyze Figure 4.

A. Hypothesize the hour at which John and Ehud ate the identical meals. How do you know? T/I

B. Hypothesize what John did at point X to change his blood sugar level. What would have happened if he had not done what he did? T/I A

C. Propose why Ehud's blood glucose level started to decrease before time X. T/I

D. Explain why both John's and Ehud's blood glucose levels began to decrease at time Y. T/I

E. Hypothesize what might have happened to decrease John's blood glucose level below Ehud's at time Z. T/I

F. Explain why it is more valid to make these kinds of comparisons between two people with the same body mass and composition, rather than two people with very different body masses and compositions. T/I

G. Describe the overall differences in Ehud's and John's blood glucose levels that these data show. T/I

Research This

Medications for Non–insulin Dependent Diabetes

Skills: Researching, Evaluating, Communicating

SKILLS HANDBOOK **A4.1, A4.2**

By now, you know that people with type 1 diabetes must have daily injections of insulin. Many people with type 2 diabetes do not need insulin injections. They are often referred to as non–insulin dependent diabetics. Their bodies still produce insulin, but either do not produce enough insulin or cannot properly use the insulin that they do produce. Some non–insulin dependent diabetics may be treated by controlling their diet and exercise. When further help is still needed, various oral medications are available to treat type 2 diabetes.

1. Research what diabetes medications are available. Use your findings to answer the following questions.

A. Under what circumstances might it be possible to manage diabetes by taking oral medications? T/I

B. What types of diabetes medications are available? T/I

C. How do diabetes medications work? T/I

D. How effective are diabetes medications at controlling diabetes? T/I

E. What are the side effects, risks, benefits, and costs of diabetes medications? T/I

F. Prepare a report, in whatever format you choose, to summarize your research. Write your report as if you are providing information for people who have just been diagnosed with diabetes. T/I C

WEB LINK

10.3 Review

Summary

- Diabetes mellitus is a disease in which the blood glucose level is not properly regulated due to a failure of insulin production or action.
- The islets of Langerhans in the pancreas secrete insulin, which lowers the blood glucose level, and glucagon, which raises the blood glucose level. The balance of insulin and glucagon regulates the concentration of glucose in the blood.
- Insulin stimulates the uptake of glucose by the cells, glycogen synthesis, the uptake of fatty acids, fat synthesis from fatty acids, and protein synthesis from amino acids.
- Glucagon raises the blood glucose level by stimulating glycogen, fat, and protein degradation. Glucocorticoids, which are secreted by the adrenal glands, can also raise the blood glucose level.
- Type 1 diabetes is caused by an inability to produce insulin, due to a failure of the beta cells in the islets of Langerhans. It tends to develop during childhood. Type 1 diabetes must be treated by injections of insulin.
- Type 2 diabetes is caused by insulin insufficiency and/or by the inability of the cells to respond correctly to insulin. It tends to develop during adulthood, often as a result of obesity. Type 2 diabetes is often treated by controlling diet and exercise.

Questions

1. What two hormones, produced by the pancreas, regulate the blood glucose level? K/U
2. What are the three classic symptoms of diabetes mellitus? K/U
3. Remember that the adrenal glands primarily produce hormones that help the body deal with stress, such as the stress of fight-or-flight situations. Why do you think the adrenal glands also produce glucocorticoids, which raise the blood glucose level? T/I
4. Describe the differences between type 1 diabetes and type 2 diabetes. K/U
5. Stress is often listed as a risk factor for weight gain or obesity. Why do you suppose that is? A
6. Canadian law requires that packaged foods display a Nutrition Facts label. T/I A
    (a) Use the Internet to research what information is listed on a Nutrition Facts label.
    (b) How can a Nutrition Facts label help a diabetic person choose foods?
7. Why might an insulin pump, which delivers constant and very small doses of insulin to the body, be preferable to insulin injections? T/I
8. Using the Internet and other sources, research some of the new developments in medicine that may lead to a cure for diabetes. Summarize your findings in a report. You are free to choose the format for your report. For example, you could choose to do a written report, an oral presentation, or a slide show. T/I C
9. Explain the principles of negative feedback using the regulation of blood sugar levels by the pancreatic hormones. K/U
10. In the past, doctors tested patients for diabetes by tasting their urine. Today, doctors have chemical tests that indicate the presence of glucose in urine. Using the Internet or other sources, research these tests. Describe two common tests and a positive result for each one. T/I

WEB LINK

Biology JOURNAL

Insulin: A Miracle Discovery

(A journal report as it may have been written by Frederick Banting and Charles Best)

SKILLS HANDBOOK A3

ABSTRACT

Even now, in the 1920s, diabetes remains one of the most difficult acquired diseases to treat. In diabetes, the blood sugar is chronically high and rises uncontrollably when a person eats. A substance we call *insulin* has been isolated and holds the promise of keeping even those patients who are very ill with diabetes alive and comfortable for many years. It is hoped that insulin will be able to save thousands or millions of lives and help people with diabetes lead a normal life.

Introduction

Oskar Minkowski and others have observed that, if the pancreas of a dog is removed, the dog contracts diabetes. This suggested that the pancreas produces a substance that stabilizes the blood sugar and keeps diabetes at bay. We have demonstrated, however, that tying off the duct through which pancreatic secretions enter the intestine results in an animal with general digestive complaints but without diabetes. These observations suggested that the substance produced by the pancreas is not released into the gut as digestive juices. Rather, it is released into the blood independently of the digestive juices.

To clarify, we hypothesized that the pancreas has two important functions: the production of digestive secretions, and the production of a substance that regulates glucose in the blood. We also hypothesized that a chemical messenger—a *hormone*—is secreted by the pancreas and controls blood glucose by a method yet undetermined. We further hypothesized that removal of this hormone from the body results in uncontrolled blood glucose levels—that is, diabetes.

Methods

Our first subject was a healthy dog. The pancreas was surgically removed, and in the days after the surgery, as the dog recovered, the glucose levels in its blood and urine rose. The dog was unusually thirsty and drank copious quantities of water, producing copious quantities of urine. It became weaker and more ill, having contracted diabetes.

Our initial thinking was that the substance secreted by the islet cells was being destroyed by the action of the digestive enzymes secreted by the pancreas. This led us to tie off the pancreatic duct of the dog, which caused the pancreas to degenerate. After several weeks, the atrophied pancreas was surgically removed and processed by partial freezing and then by grinding the tissue to obtain the internal secretion. A substance we called *isletin*, after the islets of Langerhans in the pancreas, was isolated from the filtrate.

Results

The isletin was injected into dogs that had been made diabetic by the removal of their pancreas (**Figure 1**). The injections produced a noticeable decrease in the dogs' blood sugar level and a gain in overall health. However, the effect did not last and the dogs died. Although these initial trials failed, they suggested that we had successfully isolated a substance that reduced the elevated blood sugar caused by diabetes. The challenge then was to find a method by which we could more easily obtain a supply of this substance.

Figure 1 Canadian scientists Dr. Frederick Banting (right) and Dr. Charles Best (left) discovered insulin while conducting research at the University of Toronto. Banting and his graduate supervisor, John Macleod, shared the Nobel Prize in 1923. Banting shared his prize money with his assistant, Best, whom he believed was invaluable in the quest for an agent to control diabetes.

Having nearly exhausted our supply of dogs, we were forced to produce isletin by processing the whole fresh pancreas of a dog. This extract also worked very well in reducing the blood glucose level in diabetic dogs. We realized now that the time-consuming process of tying off the pancreatic ducts to cause degeneration of the pancreas had been unnecessary. With this realization, it became much easier to generate the supply of isletin for our trials.

We now knew that a diabetic dog could be restored to health with the injection of its own isletin. We then decided to use isletin recovered from freshly slaughtered cattle to attempt to control the blood sugar of other diabetic dogs. The bovine isletin was sufficiently broad in its effects, and it kept several diabetic dogs alive for many weeks. We hypothesized that isletin (which we now call *insulin*) might have a therapeutic effect on diabetic humans. However, unpurified insulin from cattle could not be given to human subjects without ensuring its purity and sterility. Bertram Collip, who is new to this laboratory, devised a method to do just that.

Collip began using higher and higher concentrations of alcohol to dissolve the various components of the pancreatic extract. The insulin remained in solution up to a 90 % alcohol concentration, while most of the other components were precipitated out at lower concentrations. This process removed any of the other secretions of the pancreas that might affect the functioning of the insulin. At an alcohol concentration somewhere over 90 %, the insulin also precipitated and was isolated as a powder pure enough to be tested on humans.

The first human subject was a 14-year-old diabetic boy from Toronto. The boy was extremely ill, and likely near death, when dosing with insulin began. He was restored to health with regular injections of bovine insulin.

Implications

Since many cattle are slaughtered in this country every year for food, it is feasible that sufficient insulin could be recovered from bovine sources to treat all diabetic people in North America. Physicians from other nations might be trained in the recovery and administration of insulin, preventing thousands of unnecessary deaths each year.

Further Reading

Bliss, M. (1982). *The discovery of insulin.* Chicago, IL. University of Chicago Press.

Simoni, R.D., Hill, R.L., & Vaughan, M. (2002). The discovery of insulin: The work of Frederick Banting and Charles Best. *The Journal of Biological Chemistry,* 277, e15.

WEB LINK

10.4 Questions

1. What was the societal impact of the discovery of insulin by Banting and Best in 1922? K/U
2. How did Banting and Best build on prior research in their discovery of insulin? K/U
3. How did Banting and Best use dogs in their insulin research? K/U
4. Even though their initial trials failed, what did Banting and Best learn from these failures? K/U T/I
5. Why did Banting and Best change the process by which they obtained the extract from the dog pancreas? Would you consider the subsequent discovery an accident? Explain. K/U T/I
6. Explain how Bertram Collip's role was crucial in the discovery of insulin. T/I
7. (a) Considering the number of human lives that have been saved as a result of the discovery of insulin, what were the advantages and disadvantages of using dogs for the research that led to this discovery?
   (b) Do you think it was acceptable to use dogs for insulin research and to use animals for medical research in general? T/I

10.5 Steroids: Natural and Synthetic

Which of the people in **Figure 1** do you think is using steroids? Most people would assume that it is the weightlifter, not the boy with asthma. The truth is, however, that the only person we know to be using steroids, from these photographs, is the boy using the asthma inhaler. The use of illegal substances in the world of sports has led to a very negative perception of steroids. Yet, the term "steroid" refers to a class of lipids that includes cholesterol and the hormones derived from cholesterol, which act on receptors inside cells. There are many legitimate and helpful uses of steroid hormones, both in medicine and in the natural world.

Figure 1 Was your first thought that the weightlifter was using steroids? We often make false assumptions about the use and abuse of steroids.

In this section, you will learn about natural steroids and their functions in the body, as well as synthetic steroids, their legitimate medical use, and their abuse as performance-enhancing drugs in sports.

Natural Steroid Hormones

Steroid hormones act on specific target tissues in the body. Recall that target tissues are tissues with the appropriate steroid receptor molecules in the cytosol of their cells. Steroid hormones are derived from cholesterol and easily pass through the cell membrane to attach to the receptor molecules inside a cell. The hormone-receptor complex then enters the nucleus and binds to specific regulatory sequences adjacent to the genes whose expression is controlled by the hormone. This binding activates transcription, and proteins encoded by the genes are made rapidly.

All genes that are regulated by a specific steroid hormone have the same DNA sequence that binds to the hormone-receptor complex. This sequence is called a steroid hormone response element. For example, all genes controlled by a glucocorticoid have a glucocorticoid response element associated with them. Therefore, the release of a glucocorticoid into the bloodstream activates the transcription of genes through the glucocorticoid response element.

One common hormone, **testosterone**, is a steroid that helps to build muscle mass, which is one of the male secondary sex characteristics. By binding to receptors inside the cell nucleus, testosterone controls the metabolic genes that build the proteins used for muscle development. As testosterone increases, the body builds more muscle mass. This increase in muscle mass occurs naturally in the male body during puberty, but it can also be induced by the use of more testosterone.

Other natural steroid hormones include aldosterone, which is produced by the adrenal glands in response to stress, and cortisol, which is produced by the adrenal cortex and raises the blood glucose level. In females, the **estrogens** and the **progestins** are steroid sex hormones that trigger female sexual development and control the female reproductive cycle.

testosterone the main male sex hormone, which stimulates and controls the development of male secondary sexual characteristics

estrogens predominantly female sex hormones, including estradiol, that trigger sexual development

progestins predominantly female sex hormones, including progesterone, that control the menstrual cycle

Synthetic Steroids

Synthetic hormones are chemicals that have been designed to mimic the actions of natural hormones. For example, one group of synthetic hormones, called anabolic steroids, mimics many of the muscle-building characteristics of testosterone. There are many synthetic hormones that have been developed for legitimate medical purposes (**Table 1**). Synthetic steroid hormones are an important treatment for transplant patients because they suppress the immune system, reducing the incidence of organ rejection. Many synthetic steroids can reduce pain and inflammation, so they are used to treat inflammatory disorders, such as arthritis and asthma, as well as autoimmune disorders, such as lupus. Many of the prescription inhalers used to treat asthma contain synthetic steroids. Synthetic steroids used for medical purposes are considered safe and effective when used as prescribed, but they should only be used under a doctor's supervision.

synthetic hormone a hormone created by humans that behaves like a natural hormone

Table 1 Some Synthetic Steroids

Drug	Therapeutic use
prednisone	treatment of lupus and following organ transplantation
beclomethasone	treatment of asthma
dexamethasone	treatment of rheumatoid arthritis
hydrocortisone	treatment of inflammatory skin disorders

Performance Enhancement in Sports

The negative perception of steroids comes largely from the illegal use of anabolic steroids and other performance-enhancing substances in the world of sports. A small percentage of athletes are willing to risk their health and reputation to gain even a small competitive edge.

There are several ways for athletes to gain an unfair advantage. One of the most common ways is the use of anabolic steroids. These are synthetic steroids that, much like testosterone, build muscle mass. Anabolic steroids provide an advantage only in sports where muscle mass is important. In primarily aerobic sports, where greater muscle mass is less of an advantage than greater aerobic capacity, different performance-enhancing substances are used. Erythropoietin (EPO) is a protein hormone that can stimulate red blood cell production. With more red blood cells, the blood can carry more oxygen, providing longer endurance and more energy.

All of these performance-enhancing drugs have potential side effects. Anabolic steroids, in particular, have a variety of well-known negative effects, including acne, bad breath, high blood pressure, liver disease, and cancer. In men, anabolic steroids can reduce the size of the testes and enlarge the breasts. In women, they can cause irregular menstrual cycles and the growth of facial hair (**Figure 2**).

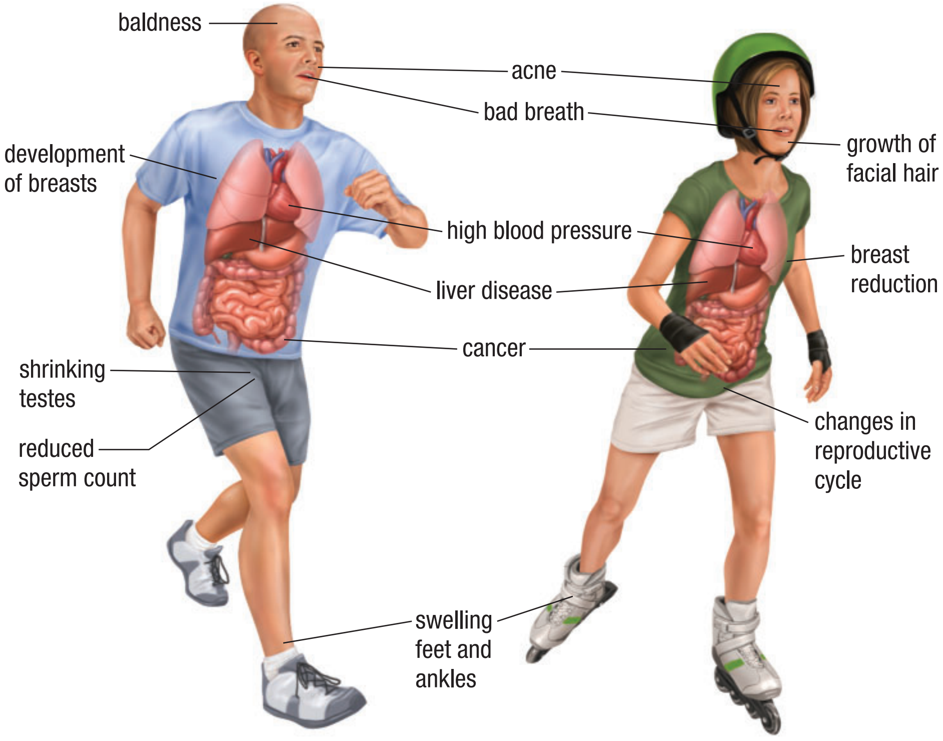


Figure 2 Negative effects of the long-term use of anabolic steroids in males and females

Some performance-enhancing drugs have a mood-altering effect. For example, anabolic steroids increase levels of aggressiveness. This "roid rage," as it is sometimes called, can lead a person to uncharacteristically violent or dangerous actions. Other drugs cause anxiety, depression, paranoia, or addiction.

Despite all the risks, there have been many high-profile cases of professional and Olympic athletes using performance-enhancing drugs. In 1988, Canadian sprinter Ben Johnson was stripped of his Olympic gold medal because of his use of unapproved substances. Baseball star Mark McGwire gained fame for hitting a record number of home runs during the 1998 season, but he later admitted to having used banned steroids to improve his hitting power. Even high school and university athletes can run into trouble by trying to unfairly enhance their performance. In June 2010, the University of Waterloo Warriors football program was suspended for a year because of the use of performance-enhancing drugs by a few of its players. Some of the players were suspended for two years.

The detection of banned substances among amateur and professional athletes is difficult, but the detection methods are continually being refined. The International Olympic Committee, for example, frequently updates its lists of banned drugs and the substances that may be used as masking agents (**Table 2**).

Table 2 International Olympic Committee List of Banned Performance-Enhancing Drugs

Drug	Advantage	Side effects
Anabolic steroids		
stanozolol, androstenediol, and nandrolone	increases muscle mass and strength	causes decreased growth, kidney problems, hair loss, oily skin, acne, shrinking testes, infertility, and cancer
Peptide hormones		
growth hormone	decreases fat and improves muscle mass	causes diabetes; abnormalities of the bones, liver, heart, and kidneys; liver disease; and high blood pressure
erythropoietin (EPO)	increases red blood cells, which carry more oxygen	thickens the blood, increasing the chance of stroke; causes heart problems
Masking agents		
bromantan	makes steroids difficult to detect	unknown
probenecid	stops the excretion of steroids for a few hours	causes headaches, tissue swelling, and nausea

The World Anti-Doping Agency (WADA) promotes and coordinates efforts against doping in all types of sports. Begun in 1999 in Switzerland, it is led by the International Olympic Committee. Canadian lawyer Richard (Dick) Pound is a former president of WADA. Because the problem of doping in sports is so serious, WADA guidelines require athletes to be available one hour each day for possible random testing for banned substances. WADA uses some very refined laboratory methods to detect banned substances. For example, the human body makes its own supply of EPO, but there is a slight chemical difference in the body's EPO and the EPO injected as a performance enhancer. WADA's sophisticated laboratories can detect the difference.

10.5 Review

Summary

- Steroids belong to a category of lipids that includes several hormones that act on receptors inside cells.
- Natural steroid hormones occur in the human body and control both male and female sexual development and reproduction, the adrenal fight-or-flight response, and the blood glucose level.
- There are many legitimate medical uses of synthetic steroids, including as painkillers and as anti-inflammatories such as those found in asthma inhalers. They should be used for a valid medical reason and must be supervised by a physician.
- There are many illegal uses of synthetic steroids, particularly in the world of sports, where some athletes are looking for any competitive edge.
- The long-term use of synthetic steroids can lead to baldness, shrinking testes, irregular reproductive cycles, and many other physical and psychological side effects.
- Many competitive sports organizations at all levels now keep lists of banned substances and conduct frequent testing to prevent athletes from using performance-enhancing drugs.

Questions

1. What are steroid hormones? K/U
2. How do steroid hormones affect DNA? K/U
3. What are synthetic hormones? K/U
4. What do the names of many steroid hormones have in common, which might allow you to recognize a steroid hormone from its name? T/I
5. Name a steroid hormone and a non-steroid hormone that affect the blood glucose level. K/U
6. Use the Internet and other sources to research the steroid called cortisone. What are some common medical uses of cortisone? What are some potential side effects of cortisone? 🌐 T/I
7. Why would it be difficult to detect the use of some banned performance-enhancing drugs, such as growth hormone, testosterone, and EPO? T/I
8. Do you think it is fair to punish an entire sports team for the actions of a few team members who used banned substances? Why or why not? T/I
9. Given what you know about negative feedback loops, what might the administration of extra testosterone do to the body of an adult male? K/U T/I
10. Anabolic steroids are sometimes used in AIDS and end-stage cancer patients. What might be the reasoning for this use? T/I
11. Choose a sport that interests you. Use the Internet and other sources to investigate examples of drug abuse associated with the sport. Write a letter to the organizing body for the sport, outlining your findings and presenting your recommendations for fixing the problem. 🌐 T/I C
12. Use the Internet and other sources to research other substances and methods that have been used in sports to provide a competitive advantage. Summarize your findings in a brief report. 🌐 T/I C
13. Proviron is a synthetic steroid hormone that has been used for performance enhancement. Using the Internet and other sources, research the medical benefits of this hormone. 🌐 T/I
14. The drugs used in inhalers to treat asthma can be grouped into relievers (short-acting bronchodilators), preventers (steroid inhalers), and long-acting bronchodilators. Using the Internet and other sources, find out how these drugs work. Create a poster or other visual presentation that explains the differences in the actions of these drugs. 🌐 T/I C

🌐 WEB LINK

10.6 Explore an Issue in Synthetic Steroids

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

The Cost of Performance-Enhancing Drug Use

Large amounts of money and fame are at stake in the world of sports. As a result, some athletes are willing to ignore the risks of using performance-enhancing drugs (PEDs). Most people probably think of anabolic steroids when they hear the term "performance-enhancing drugs," but there are many other hormones, drugs, and techniques that can be used to get a competitive edge in sports. For example, erythropoietin (EPO) and blood doping can enhance performance in aerobic sports such as running and cycling (**Figure 1**). Painkillers and anti-inflammatory drugs can also enhance performance by allowing the athlete to "play through the pain." Other drugs, such as beta blockers and caffeine, can lower or raise the heart rate and raise alertness for better performance in particular sports.

Figure 1 Participants in long bicycle races can gain an advantage by having more red blood cells to carry oxygen as they compete.

The Issue

Some competitive athletes, as well as others who want peak physical performance, resort to drugs as a way to boost their body's natural abilities. Many defend the practice by claiming that performance-enhancing drug (PED) use is so widespread, it is impossible to compete at an elite level without the advantage these drugs offer. Are the benefits of these drugs worth the potential physical, psychological, ethical, medical, social, and legal risks involved?

The issue of PEDs can be examined from many perspectives, including those of an athlete, a coach, a fan, a parent, a doctor, a sport psychologist, and a fitness trainer. Moreover, different sports (and different levels of these sports) have different considerations. Drugs that benefit weightlifters might do more damage to the body than drugs that benefit aerobic athletes.

Goal

To conduct research about steroid PEDs and their advantages and disadvantages, and to make a personal decision about whether the risks associated with these drugs outweigh the potential benefits

Research

SKILLS HANDBOOK A4

Select a particular sport or area of sports, and an audience that you would like to use as a focus for your research. Investigate the various steroid PEDs used in that sport at that level. Consider the following questions:

- What types of drugs are used as performance enhancers? Which of these drugs are legal but banned? Which are illegal?
- How do these PEDs work?
- What are the known side effects of these PEDs?
- What are the potential benefits and risks of using these PEDs?
- What are the short-term and long-term health concerns associated with using these PEDs?
- Other than potential health risks, how might the use of PEDs affect a person's life?
- What are the implications for the sport you chose? What are the broader implications for society? WEB LINK

Possible Solutions

Use the results of your research to weigh all the possible solutions and answer the following questions:

- Is the use of PEDs justified in the sport you researched, based on the perspective you chose?
- Is there any middle ground on this issue, or is the answer clear-cut?

Decision

Take a position on whether PEDs should be used in the sport you researched, based on the perspective you chose. Base your decision on solid scientific evidence. Be prepared to back up your decision with this evidence and with sound reasoning.

Communicate

Choose one of the following formats to present your position:

- Prepare and hold a debate in your class to present opposing viewpoints concerning the use of PEDs. Present solid scientific evidence and use sound reasoning to support your position about the use of PEDs.
- Write a letter to a government agency that regulates a particular sport, presenting your opinion and suggestions about the use of PEDs.

Plan for **Action**

How can you use what you have learned about PEDs? Here are two ideas:

- Conduct a survey in your school to determine students' knowledge and opinions about the use of PEDs in sports. Present the results of your survey to your school administration or parents.
- Find out who in your community might be interested in a discussion about the use of PEDs. It might be a group of high school students, an amateur athletic club, the governing body for a professional sport, or a government agency. If you were the local Chief Medical Officer, how might you reach out to students, athletes, and organizations, as well as to parents and the public, to have a discussion about PEDs as a community? Develop a plan for presenting your research to your intended audience.

10.7 The Reproductive Hormones

gonads glands responsible for the production of sex hormones, as well as the egg and sperm cells; called testes in males and ovaries in females

androgens predominantly male sex hormones, including testosterone, that control sexual development and reproduction

The reproductive system in vertebrates involves separate male and female reproductive systems. The sex glands or **gonads**—the testes in males and the ovaries in females—are the primary source of sex hormones. The steroid hormones that they produce—the **androgens,** estrogens, and progestins—have similar functions in regulating the development of male and female reproductive systems, sexual characteristics, and mating behaviour. Both males and females produce all three types of hormones, but in different proportions. Androgen production is predominant in males, whereas estrogen and progestin production is predominant in females.

The Female Reproductive System

gonadotropin-releasing hormone (GnRH) a hormone released by the hypothalamus that controls the release of LH and FSH from the anterior pituitary, which, in turn, control the synthesis and release of the male or female sex hormones in the gonads

Human females have a pair of ovaries (singular: *ovary*) suspended in the abdominal cavity (**Figure 1**). As well as producing the female gametes (*ova*, or *eggs*), the ovaries produce estrogens, which are steroid hormones that stimulate and control the development and maintenance of the female reproductive system. The principal estrogen, called estradiol, stimulates the maturation of the sex organs at puberty; the development of secondary sexual characteristics such as breast development, the growth of body hair, and the widening of the pelvis; and the development of the sex drive. The ovaries also produce progestins. The main progestin is progesterone, which is the steroid hormone that prepares and maintains the uterus for the implantation of a fertilized egg and the subsequent growth and development of an embryo. The synthesis and secretion of progesterone by cells in the ovaries are controlled by the release of follicle-stimulating hormone (FSH) from the anterior pituitary. The release of FSH and luteinizing hormone (LH) is controlled by **gonadotropin-releasing hormone (GnRH)** from the hypothalamus. CAREER LINK

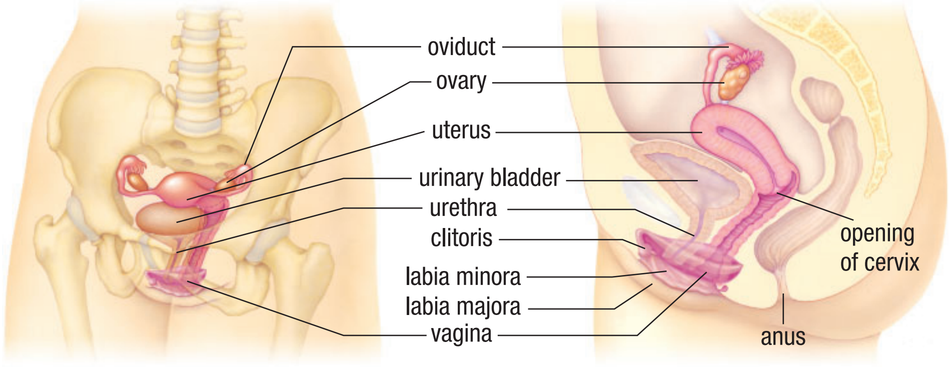


Figure 1 The reproductive organs of a human female

An oviduct leads from each ovary to the uterus. The uterus is a hollow structure with walls that contain smooth muscle. It is lined by the endometrium, which is formed by layers of connective tissue with embedded glands and a rich supply of blood vessels. If an egg is fertilized and begins to develop, it must implant in the endometrium to continue developing. The lower end of the uterus, called the cervix, opens into a muscular canal, called the vagina, which leads to the exterior. Sperm enter the female reproductive tract through the vagina. At birth, the baby passes from the uterus through the vagina to the outside.

oogenesis the production of eggs, or ova, from oocytes in the ovaries by two meiotic divisions

The process by which the ovaries produce and release eggs, or ova, is called **oogenesis** and is controlled by hormones produced by the pituitary gland. In some animals, including humans, the ovary does not release mature eggs. Instead, it releases oocytes, which are immature eggs that have undergone only their first meiotic division. An oocyte finishes the first meiotic division to become a secondary oocyte and a non-functional, underdeveloped cell called a polar body. Even before a female infant is born, each of her ovaries contains about one million oocytes whose development is arrested at the end of the first meiotic prophase. Although 200 000 to 380 000 oocytes survive until a female reaches sexual maturity, only about 380 oocytes are actually ovulated before **menopause**, the end of a female's reproductive capability. Ovulation is the monthly release of one or a few developing oocytes into the nearby oviduct. Once ovulated, an ovum is pulled through the oviduct by a current produced by the beating of the cilia that line the oviduct. The cilia propel the egg along the oviduct, where fertilization may occur. The second meiotic division occurs only if the oocyte is penetrated by a sperm. When this happens, a mature ovum and a polar body form, and the nucleus of the ovum immediately fuses with the nucleus of the sperm to form a fertilized egg, or zygote. The zygote is propelled into the uterus by the cilia of the oviduct. If the ovum is not fertilized, it degenerates and disappears.

menopause the end of a female's reproductive capability, after which menstruation ceases and female hormone levels drop

In most vertebrates, ovulation occurs during a well-defined mating season. Humans, however, do not show any evidence of a mating season. Mating and fertilization can occur at any time of the year. Furthermore, women do not generally know when they are ovulating, and neither do their partners.

Reproduction in human females is under neuroendocrine control. It involves complex interactions between the hypothalamus, pituitary gland, ovaries, and uterus. The ovarian cycle occurs from puberty to menopause and involves the events in the ovaries that lead to the release of a mature egg approximately every 28 days. The ovarian cycle is coordinated with the **menstrual cycle** (from *menses* meaning "month")—the monthly cycle of events in the uterus that prepare the uterus to implant the egg if fertilization occurs (**Figure 2**, next page).

menstrual cycle the monthly cycle of events in a sexually mature female that prepares the uterus for the implantation of a fertilized egg

The beginning of the ovarian cycle is stimulated by the release of GnRH by the hypothalamus. GnRH stimulates the pituitary to release follicle-stimulating hormone (FSH) and luteinizing hormone (LH) into the bloodstream. FSH stimulates 6 to 20 oocytes in the ovaries to begin meiosis. As the oocytes develop, they become surrounded by cells that form a follicle (the ovum and follicle cells). During this phase, the follicle grows and develops. At its largest size, it becomes filled with fluid and may be 12 to 15 mm in diameter. Usually, only one follicle develops to maturity, with the release of the egg by ovulation. Multiple births can result if two or more follicles develop and their eggs ovulate and are fertilized in one cycle.

As the follicle enlarges, FSH and LH interact to stimulate estrogen secretion by the follicular cells. Initially, the estrogens are secreted in low amounts and have a negative feedback effect on the pituitary, inhibiting the secretion of FSH. As a result, the FSH secretion declines briefly. However, estrogen secretion increases steadily, and its level peaks about 12 days after the beginning of follicle development. A high estrogen level has a positive feedback effect on the hypothalamus and pituitary, increasing the secretion of GnRH and stimulating the pituitary to release a burst of FSH and LH.

Ovulation occurs after the burst in LH secretion stimulates the follicle cells to release enzymes that digest the wall of the follicle, causing it to rupture and release the egg. LH also causes the follicle cells that remain at the surface of the ovary to grow into an enlarged, yellowish structure called the corpus luteum (from *corpus* meaning "body" and *luteum* meaning "yellow"). This initiates the luteal phase, which prepares the uterus to receive a fertilized egg. The corpus luteum acts as an endocrine gland that secretes estrogens, as well as large quantities of progesterone and another hormone called inhibin. Progesterone stimulates the growth of the uterine lining and inhibits contractions of the uterus. Progesterone and inhibin have a negative feedback effect on the hypothalamus and pituitary gland. Progesterone inhibits the secretion of GnRH and, in turn, the secretion of FSH and LH by the pituitary gland. Inhibin specifically inhibits FSH secretion. The decrease in FSH and LH levels diminishes the signal for follicular growth, so no new follicles begin to grow in the ovary.

If fertilization does not occur, the corpus luteum gradually shrinks, perhaps because of the low level of LH. About 10 days after ovulation, the shrinkage of the corpus luteum inhibits the secretion of estrogen, progesterone, and inhibin. In the absence of progesterone, menstruation begins. As progesterone and inhibin levels decrease, FSH and LH secretion is no longer inhibited and a new monthly cycle begins.

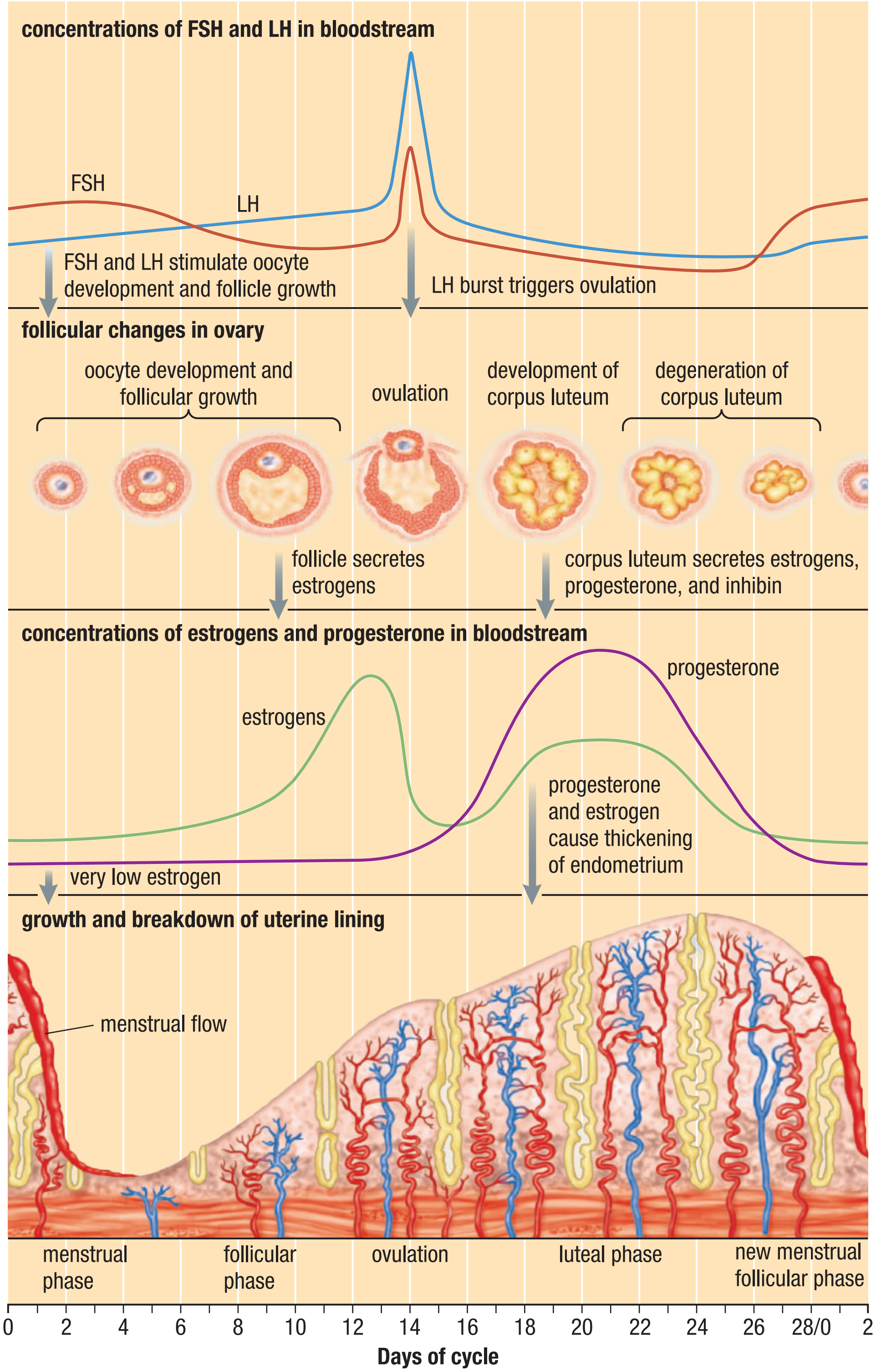

concentrations of FSH and LH in bloodstream
FSH
LH
FSH and LH stimulate oocyte development and follicle growth
LH burst triggers ovulation
follicular changes in ovary
oocyte development and follicular growth
ovulation
development of corpus luteum
degeneration of corpus luteum
follicle secretes estrogens
corpus luteum secretes estrogens, progesterone, and inhibin
concentrations of estrogens and progesterone in bloodstream
estrogens
progesterone
progesterone and estrogen cause thickening of endometrium
very low estrogen
growth and breakdown of uterine lining
menstrual flow
menstrual phase
follicular phase
ovulation
luteal phase
new menstrual follicular phase
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28/0
2
Days of cycle

Figure 2 The ovarian and menstrual cycles of a human female

The Menstrual Cycle

The menstrual cycle involves the changes in the uterus over one ovarian cycle. The same hormones that control the ovarian cycle also control the menstrual cycle, physiologically connecting the two processes. Day 0 of the monthly cycle is the beginning of follicular development in the ovary and the beginning of menstrual flow in the uterus. Menstrual flow results from the breakdown of the endometrium, which releases blood and tissue breakdown products from the uterus to the outside through the vagina.

When the flow ceases (at day 4 or 5 in the cycle), the endometrium begins to grow again. As the endometrium gradually thickens, oocytes in both ovaries begin to develop further, eventually leading to ovulation (usually a single egg from one ovary) at about 14 days into the cycle. The uterine lining continues to grow for another 14 days after ovulation. At this time, if fertilization has not taken place, the absence of progesterone results in the contraction of the arteries that supply blood to the uterine lining, shutting down the blood supply and causing the lining to disintegrate. The menstrual flow begins. Contractions of the uterus, no longer inhibited by progesterone, help to expel the debris. Prostaglandins released by the degenerating endometrium add to uterine contractions, making them severe enough to be felt as painful cramps and sometimes producing other effects, such as nausea, vomiting, and headaches.

The monthly cycle of high levels of sex hormones eventually stops in later adulthood, usually when a woman is in her late 40s or early 50s, during a period called menopause. The menstrual cycle also stops at this time. The great reduction in estrogens can produce undesirable side effects, including hot flashes, headaches, and mood swings. These symptoms can be reduced by hormone replacement therapy (HRT). HRT supplies an outside source of estrogen, either through oral medication or a skin patch. While HRT has many benefits, the treatment has become controversial in recent years because of the increased risk of heart disease, breast cancer, and stroke.

Menstruation occurs only in human females and in our closest primate relatives, gorillas and chimpanzees. In other mammals, the uterine lining is completely reabsorbed if a fertilized egg does not implant during the period of reproductive activity. The uterine cycle in these mammals is called the estrous cycle, and females are said to be in estrus when fertile.

Investigation 10.7.1

Hormone Levels during the Ovarian and Menstrual Cycles (p. 504)
You now understand the stages of the ovarian and menstrual cycles. This investigation will help you understand the relative levels of the various hormones throughout the menstrual cycle.

Fertilization and Pregnancy

Inside the human body, an egg can be fertilized only during its passage through the third of the oviduct that is nearest the ovary. If the egg is not fertilized during the 12 to 24 h it is in this location, it disintegrates and dies. To fertilize the egg, sperm cells must first penetrate the layer of follicle cells surrounding the egg (**Figure 3**). As soon as the first sperm cell reaches the egg, the sperm and egg plasma membranes fuse, the tail of the sperm is detached, and the head of the sperm cell is engulfed by the cytosol of the egg.

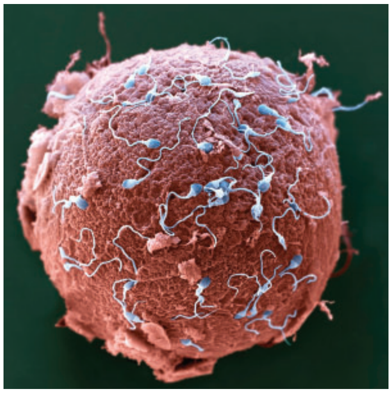


Figure 3 A human egg cell (ovum), surrounded by sperm cells

Membrane fusion activates the egg. The sperm that enters the egg releases nitric oxide, stimulating the release of stored Ca^{2+} in the egg. The Ca^{2+} prevents other sperm from reaching the plasma membrane of the egg and triggers the completion of meiosis of the egg. The sperm and egg pronuclei then fuse, and the cell becomes the zygote. Mitotic divisions of the zygote soon initiate embryonic development.

The first cell divisions of embryonic development take place in the oviduct. About seven days after ovulation, the embryo passes from the oviduct and implants in the uterine lining. During and after implantation, cells associated with the embryo secrete human chorionic gonadotropin (hCG), a hormone that keeps the corpus luteum in the ovary from breaking down. It also suppresses the mother's immune system to prevent it from rejecting the embryo. Excess hCG is excreted in the urine. Its presence in the urine or blood provides the basis of pregnancy tests. After implantation, the embryo begins to grow more rapidly, and a placenta forms. The placenta is an organ formed from the uterine lining with membranes from the uterus. It supports the growth of the embryo.

Continued activity of the corpus luteum keeps estrogen and progesterone secretion at high levels, which maintains the uterine lining and prevents menstruation. The high progesterone level also thickens the mucus secreted by the uterus, forming a plug that seals the opening of the cervix from the vagina. The plug keeps bacteria, viruses, and sperm cells from further copulations from entering the uterus.

About 10 weeks after implantation, the placenta takes over the secretion of progesterone, hCG secretion drops off, and the corpus luteum regresses. However, the corpus luteum continues to secrete the hormone relaxin, which inhibits the contraction of the uterus until near the time of birth. CAREER LINK

The Male Reproductive System

The male sex hormones affect the development of the male secondary sex characteristics. If you have ever had a pet that was neutered at a young age, you may have noticed differences in its development compared with the development of animals that were not neutered. For example, neutered cats and dogs may grow larger and fatter. Neutered animals generally have a milder temperament than unneutered animals, as well. For centuries, farmers have castrated livestock (removed their testes) in order to have animals with a milder temperament, greater body mass, and fattier meat. A steer, which most beef comes from, is a castrated bull. There are even historical examples from around the world of castration being used on humans for various purposes: choir boys were once castrated to maintain their high voices, eunuchs who supervised harems were castrated, and criminals and mental patients were sometimes castrated as a punishment or treatment.

The testes (singular: *testis*) of male vertebrates secrete androgens, which are steroid hormones that stimulate and control the development and maintenance of the male reproductive system. The principal androgen is testosterone, the male sex hormone. In young adult males, a jump in the testosterone level stimulates puberty and the development of secondary sexual characteristics, including the growth of facial and body hair, muscle development, changes in the vocal cords, and the development of the sex drive. The synthesis and secretion of testosterone by cells in the testes are controlled by the release of LH from the anterior pituitary gland. The release of LH is controlled by GnRH from the hypothalamus, the same hormone that regulates the sex hormones in females.

spermatogenesis the production and development of sperm cells in the testes

Testosterone also controls **spermatogenesis**, the process by which sperm cells are produced in the testes from precursor cells called spermatogonia. The organs that produce and deliver sperm make up the male reproductive system (**Figure 4**). Human males have a pair of testes suspended in a baglike scrotum, which serves to regulate their temperature. In human males, each testicle is packed with about 125 m of seminiferous tubules, in which sperm proceed through all the stages of spermatogenesis.

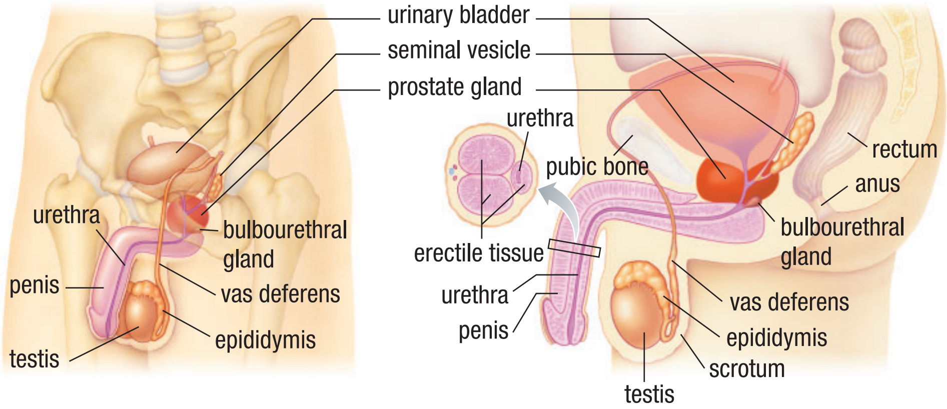


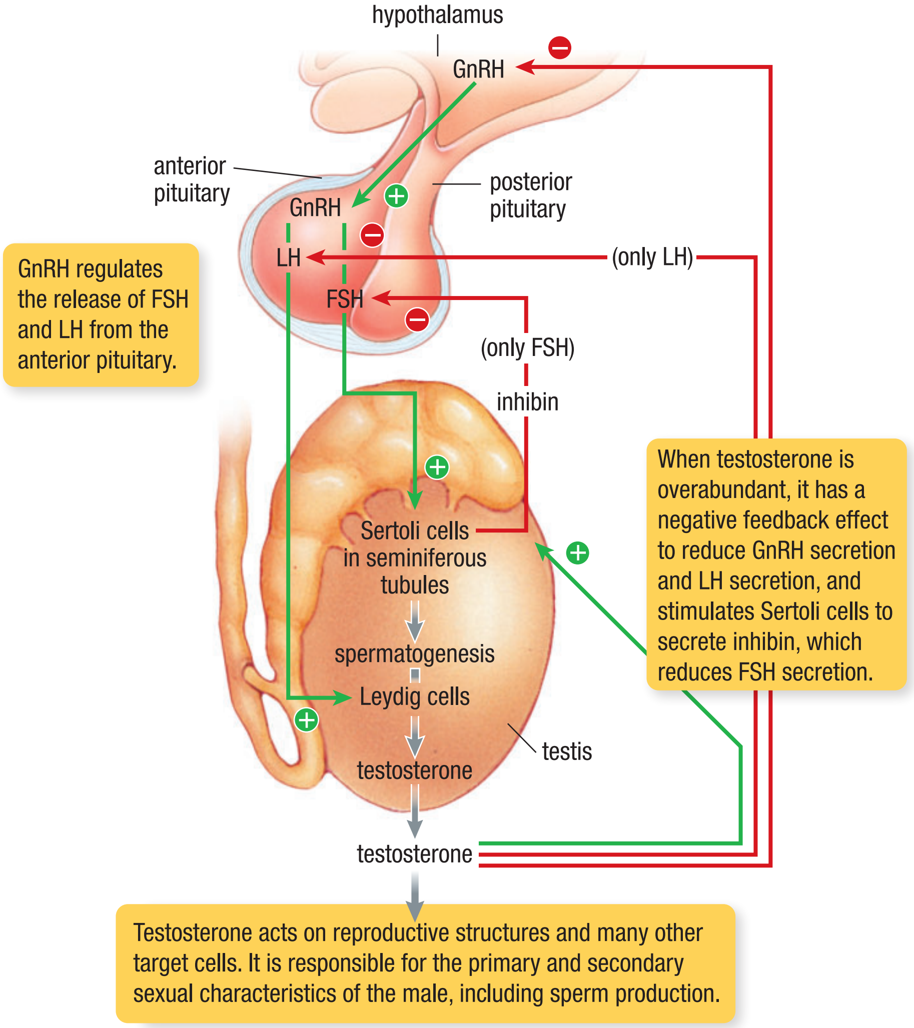
Figure 4 The reproductive organs of a human male

The entire process, from spermatogonium to sperm, takes 9 to 10 weeks. The testes produce about 130 million fertile sperm each day. This number varies among men. In the last 50 years, however, the average sperm count of men has fallen, sometimes to a level that makes it difficult for couples to conceive. While scientists agree that the average sperm count has fallen, there is no clear cause. Some evidence points to chemicals in the environment that mimic hormones in the body. It may be a male's exposure during prenatal development, rather than his exposure after birth, that affects his sperm count.

Sertoli cells are supportive cells that completely surround the developing spermatocytes in the seminiferous tubules. They supply nutrients to the spermatocytes and seal off the spermatocytes from the body's blood supply. Leydig cells, located in the tissue surrounding the developing spermatocytes, produce the male sex hormones (androgens), particularly testosterone.

Mature sperm flow from seminiferous tubules into the epididymis, which is a coiled storage tubule attached to the surface of each testis. Rhythmic muscular contractions of the epididymis move sperm into a thick-walled, muscular tube, the vas deferens (plural: *vasa deferentia*), which extends through the abdominal cavity.

Many of the hormones that regulate the menstrual cycle, including GnRH, FSH, LH, and inhibin, also regulate the male reproductive functions. Testosterone, secreted by the Leydig cells in the testes, also plays a key role (**Figure 5**). In sexually mature males, the hypothalamus secretes GnRH in brief pulses every one to two hours. GnRH stimulates the pituitary gland to secrete LH and FSH. LH stimulates the Leydig cells to secrete testosterone, which stimulates sperm production and controls the growth and function of the male reproductive structures. FSH stimulates Sertoli cells to secrete a protein and other molecules required for spermatogenesis.



GnRH regulates the release of FSH and LH from the anterior pituitary.

When testosterone is overabundant, it has a negative feedback effect to reduce GnRH secretion and LH secretion, and stimulates Sertoli cells to secrete inhibin, which reduces FSH secretion.

Testosterone acts on reproductive structures and many other target cells. It is responsible for the primary and secondary sexual characteristics of the male, including sperm production.

Figure 5 The hormonal regulation of reproduction in the male, and the negative feedback systems that control the hormone levels

Concentrations of the male reproductive hormones are maintained by negative feedback mechanisms (Figure 5). If the concentration of testosterone falls in the bloodstream, the hypothalamus responds by increasing GnRH secretion. If the concentration of testosterone becomes too high, the overabundance inhibits LH secretion. An overabundance of testosterone also stimulates Sertoli cells to secrete inhibin, which inhibits FSH secretion by the pituitary gland. As a result, testosterone secretion by the Leydig cells drops off, returning the concentration to optimal levels in the bloodstream. CAREER LINK

Controlling Reproduction with Hormones

Knowledge about the details of reproduction can allow us to control fertility. In some cases, this means increasing the chance of reproducing. In other cases, it means minimizing the chance. Knowledge about the timing of ovulation, for example, can provide a way to maximize or minimize the chance of pregnancy.

Hormonal birth control involves administering estrogen and/or progesterone, or chemical mimics of these hormones, to females in carefully controlled doses throughout the month in order to control the menstrual cycle and prevent ovulation. These hormones may be given as pills, injections, or patches, or as an implant that slowly releases hormones into the bloodstream.

Side effects are a concern when hormones are used for birth control. Birth control pills are usually considered safe and effective, but if they are used inappropriately side effects may include nausea and weight gain, lighter periods, or sore breasts. More rarely, women may experience headaches; blurred vision; or pain in the chest, abdomen, or thighs. Older women, particularly smokers with a history of cardiovascular problems, may be at increased risk for heart or liver disease, thromboses, or breast or uterine cancer.

There are also concerns about the long-term environmental impact of hormonal birth control use, or the use of any hormonal medications. Birth control pills contain estrogen and/or progestin. These hormones end up in the environment and possibly in drinking water. Human urine in wastewater, farm-waste runoff, flushing or dumping of prescription medications, and the use and disposal of products that we purchase all contribute to the presence of hormones and potentially harmful chemicals in our environment. Some pesticides and plastics have been shown to contain chemicals that mimic the effects of estrogen or block actions of the endocrine system, raising concerns about risks to human health.

Research This

Assessing the Risks of Bisphenol A

Skills: Researching, Analyzing, Evaluating, Communicating, Defining the Issue, Defending a Decision

SKILLS HANDBOOK **A4.1**

Many chemicals in the environment have impacts on plants and animals, including humans. Some of these effects are known, but some are still unknown and under investigation. Some chemicals supplement the effects of hormones that are naturally produced in the body. Other chemicals mimic the effects of hormones such as estrogen. Chemicals known as endocrine disruptors (or endocrine-disrupting compounds, EDCs) interfere with the normal functions of the endocrine system.

One of the most well-known and widespread chemicals that can affect the endocrine system is bisphenol A, known as BPA. BPA is a chemical that has been widely used in the production of hard plastic food and beverage containers and can liners. Trace amounts of BPA can be found in the food that comes in these containers.

1. Investigate and identify current scientific research on the potential link between BPA and human health problems. Investigate the extent of its use in plastic production. In particular, compare positions taken by governments, industries, and scientific researchers.

A. Make and justify a personal decision about the use of BPA. T/I A

B. What potential effects does BPA have on human health? T/I

C. Describe the possible link between BPA and the falling sperm count in males over the past half century. T/I

D. What will you do or not do to avoid any potential risks of BPA to your own health? Consider the idea of “the absence of evidence versus the evidence of absence.” Can you distinguish between the two in researching this issue? Consider the risk associated with drawing conclusions based on the absence of evidence. If there is no evidence that BPA is a dangerous substance, can you reasonably conclude that BPA is not a dangerous substance? K/U A

E. Prepare a report, in a format of your choice, that summarizes your research on this issue, identifies how BPA gets into the human body, summarizes the potential health risks associated with BPA, and compares these risks with other everyday risks. T/I C

F. Write a letter to Health Canada, either supporting or criticizing the decision to identify BPA as a toxic substance. Provide evidence to support your position. C

WEB LINK

10.7 Review

Summary

- Reproduction is controlled by the sex hormones, which are primarily produced in the gonads: the testes in males and the ovaries in females.
- Testosterone is the primary sex hormone in males, and estrogen is the primary sex hormone in females. These hormones control the development of the secondary sexual characteristics and the sex drive.
- Follicle-stimulating hormone (FSH) is released by the pituitary gland in response to gonadotropin-releasing hormone (GnRH) from the hypothalamus. FSH stimulates the development of oocytes in the ovaries.
- Ova (eggs) are produced from oocytes in a process called oogenesis. Once an oocyte is released during ovulation, it travels along the oviduct. There, it may become fertilized by a sperm cell. The developing embryo then travels to the uterus, where it implants.
- The menstrual cycle prepares the uterus to receive the fertilized egg. The hormones estrogen and progesterone carefully control the menstrual cycle to go along with the ovarian cycle and prepare the body for pregnancy.
- Spermatogenesis, the production of sperm in the testes of the male, is controlled by the male androgen hormone testosterone. Males produce sperm constantly, at a rate of about 130 million per day.
- The manipulation of hormones in females can be used to control reproduction.

Questions

1. What are the main male and female sex hormones? Describe their functions. K/U
2. What is the relationship between the ovarian cycle and the menstrual cycle? Explain how reproduction is determined by these two cycles. K/U
3. Use a flow chart or another graphic organizer to explain the main steps in the menstrual cycle. K/U C
4. Research the risks and benefits of hormone replacement therapy (HRT) in menopausal women. What are some of the risks of HRT? T/I C
5. Construct a flow chart that shows the events leading up to the implantation of an embryo in the uterus. Begin with the ripening of a follicle in the ovary. K/U C
6. Name three hormones common to both males and females that regulate both the menstrual cycle and the male reproductive functions. K/U
7. How does the sexual cycle of human females differ from the sexual cycle of other vertebrates? K/U
8. What result would you expect if a fertilizing sperm cell did not released nitric oxide when it entered an egg? Why? K/U A
9. How are the effects of testosterone on males and estrogen on females similar? K/U
10. What is the importance of human chorionic gonadotropic hormone (hCG)? K/U
11. A woman discovers that she is not ovulating. Which endocrine glands might a doctor suspect are not functioning properly? Explain your answer. K/U T/I
12. Estrogen and progesterone are no longer produced when a woman reaches menopause. Which body systems do you think could be affected by these changes in hormonal production? Explain your choices. K/U T/I

WEB LINK

Investigation 10.7.1 OBSERVATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Hormone Levels during the Ovarian and Menstrual Cycles

In this investigation, you will carefully analyze the simultaneous changes of several different hormones that govern the female reproductive cycle. The data used in this investigation are based on real physiological data from a female of reproductive age.

Purpose

To observe how the levels of various hormones change during the ovarian and menstrual cycles

Procedure

SKILLS HANDBOOK A2.1, A2.4, A5.4

1. Analyze the data in each figure, table, and graph. These data illustrate the changes in hormones during the menstrual cycle. Steps 3 to 6 will help you focus your analysis.
2. As you analyze the data, make detailed notes. You will need to use these notes when you answer the Analyze and Evaluate questions.

Part A: Ovarian Hormones in the Ovarian Cycle

3. Study the feedback loops shown in **Figure 1**. Determine which hormone is represented by each letter. Record your observations.

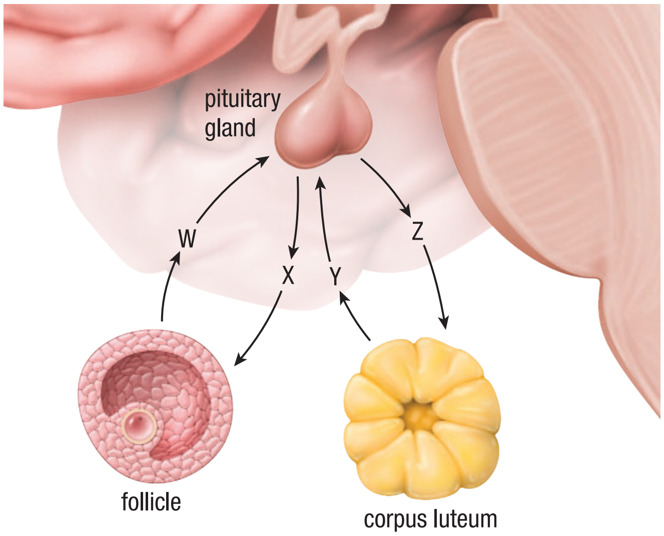


Figure 1 Regulation of ovarian hormones by gonadotropic hormones via a feedback loop

Part B: Ovulation

4. **Table 1** shows the body temperatures of two different women during the menstrual cycle: one woman ovulated during this cycle, and one did not. Study the data in the table, identifying the differences between the two sets of temperatures. Record your observations carefully.

Table 1 Body Temperatures during the Menstrual Cycle

	Temperature (°C)	
Days	**Ovulation occurs**	**No ovulation occurs**
5	36.4	36.3
10	36.2	35.7
12	36.0	35.8
14	38.4	36.2
16	37.1	36.1
18	36.6	36.0
20	36.8	36.3
22	37.0	36.3
24	37.1	36.4
28	36.6	36.5

Part C: Changes in the Endometrium

5. **Figure 2** (next page) is a graph of the thickness of the endometrium throughout the menstrual cycle. Study the graph to determine what occurred at each lettered point. Record all of your observations.

Part D: Hormone Levels During the Menstrual Cycle

6. **Figure 3** (next page) is a graph of the levels of LH, FSH, estrogen, and progesterone throughout the menstrual cycle. Study the graph, and interpret the data for each hormone level. Record your observations.

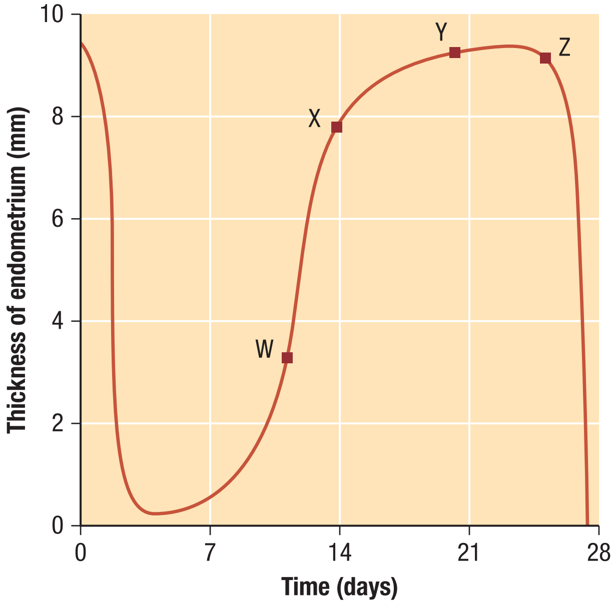


Figure 2 Graph of thickness of endometrium throughout the menstrual cycle

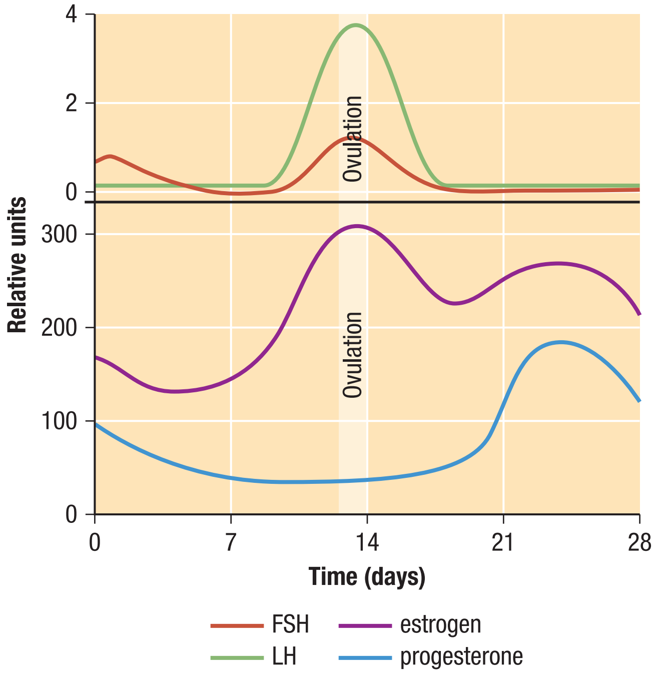


Figure 3 Graph of hormone levels (LH, FSH, estrogen, and progesterone) throughout the menstrual cycle

Analyze and Evaluate

(a) Name the two gonadotropic hormones, and state the letters that represent them in Figure 1. K/U T/I

(b) Name the ovarian hormones, and state the letters that represent them in Figure 1. K/U T/I

(c) Which of the hormones that you identified in Figure 1 are responsible for producing negative feedback to suppress the secretion of the other hormones? K/U

(d) Construct a graph from the data given in Table 1. How will you label your horizontal and vertical axes? How will you distinguish between the two different situations? T/I C

(e) On which day did ovulation occur, assuming that the data on your graph represent a typical 28-day menstrual cycle? How do you know? Label on your graph the day that ovulation occurred. T/I C

(f) How did body temperature change before and after ovulation? T/I

(g) Compare the changes in body temperature for the two women. Note that one woman had an active corpus luteum and the other woman did not. T/I C

(h) What events occurred at the times labelled X and Z on the graph in Figure 2? T/I

(i) At what point on the graph did the follicle cells produce estrogen? T/I

(j) At what point on the graph did the corpus luteum produce estrogen and progesterone? T/I

(k) Looking only at the graph in Figure 3, is there any evidence that the levels of estrogen or progesterone were influenced by the sudden peak in the production of LH? T/I

(l) Ovulation tests check for a rise in a certain hormone that signals ovulation. Which of the hormones shown in Figure 3 underwent a change that would be extreme enough for an over-the-counter test to detect? T/I

(m) Examine Table 1 and the graph you constructed in question (d) alongside Figure 3. With which hormone level does body temperature track most closely? A

Apply and Extend

(n) A woman who has given birth to triplets has two corpus lutea in her ovaries. Explain how this could happen. T/I

(o) Estrogen plays an important role in maintaining bone density. Research health problems that are faced by post-menopausal women due to changes in the estrogen level. How do lifestyle factors contribute to these health problems? What treatments are available? T/I C A

(p) Steroid hormones are often given to cattle and other farm animals to build body mass and thus increase meat production. There is some concern that these hormones may lead to side effects in humans who eat meat or drink milk from these animals. What effects do you think steroids given to cattle may have on humans? T/I C

WEB LINK

CHAPTER 10 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts in the margin on page 466. For each point, write three or four sub-points that provide further information and explanations, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 466. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How has your understanding changed?

Vocabulary

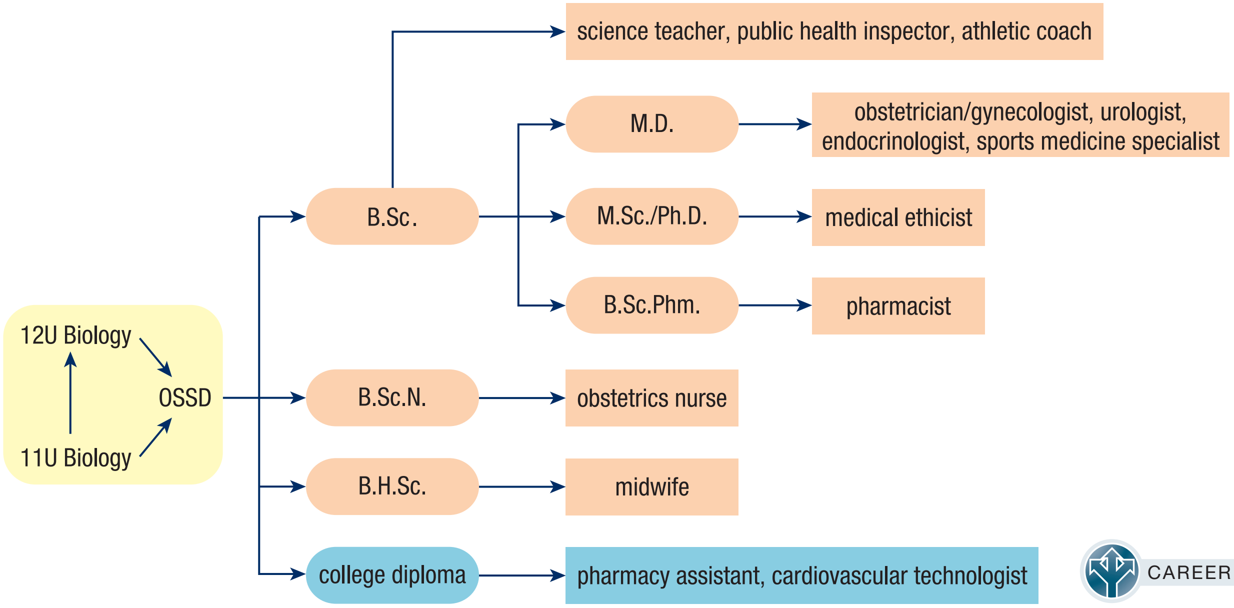
protein hormone (p. 469)
steroid hormone (p. 469)
glucagon (p. 469)
hypothalamus (p. 473)
neurohormone (p. 473)
pituitary gland (p. 474)
thyroid gland (p. 478)
parathyroid hormone (p. 479)
pineal gland (p. 480)
islets of Langerhans (p. 483)
testosterone (p. 490)
estrogens (p. 490)
progestins (p. 490)
synthetic hormone (p. 491)
gonads (p. 496)
androgens (p. 496)
gonadotropin-releasing hormone (GnRH) (p. 496)
oogenesis (p. 496)
menopause (p. 497)
menstrual cycle (p. 497)
spermatogenesis (p. 500)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to the endocrine system that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.



science teacher, public health inspector, athletic coach
M.D.
obstetrician/gynecologist, urologist, endocrinologist, sports medicine specialist
B.Sc.
M.Sc./Ph.D.
medical ethicist
B.Sc.Phm.
pharmacist
12U Biology
OSSD
11U Biology
B.Sc.N.
obstetrics nurse
B.H.Sc.
midwife
college diploma
pharmacy assistant, cardiovascular technologist

CAREER LINK

CHAPTER 10 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. What are the products of the endocrine glands? (10.1) K/U
   (a) enzymes
   (b) hormones
   (c) ions
   (d) minerals
2. What is the function of the endocrine system? (10.1) K/U
   (a) It produces hormones that are secreted in the digestive tract.
   (b) It releases hormones as rapidly as nerve impulses are transmitted.
   (c) It releases hormones into the bloodstream or into the fluid around the cells.
   (d) It releases only water-soluble hormones.
3. Where is the pituitary gland located? (10.2) K/U
   (a) in the abdominal cavity
   (b) in the tissues in the neck
   (c) within the cranium, just below the brain
   (d) along the femoral artery
4. Which of the following endocrine glands is a direct extension of the nervous system? (10.2) K/U
   (a) anterior pituitary gland
   (b) posterior pituitary gland
   (c) thyroid gland
   (d) hypothalamus
5. What is the target tissue of ACTH? (10.2) K/U
   (a) adrenal cortex
   (b) thymus gland
   (c) beta cells of the pancreas
   (d) mammary glands
6. Which statement about the effects of diabetes mellitus is true? (10.3) K/U
   (a) The placenta does not produce progesterone.
   (b) The hypothalamus does not function.
   (c) Insufficient calcium enters the cells.
   (d) Insufficient glucose enters the cells.
7. Which hormones are secreted by the islets of Langerhans in the pancreas? (10.3) K/U
   (a) insulin and oxytocin
   (b) insulin and calcium
   (c) insulin and thyroxin
   (d) insulin and glucagon
8. Insulin and glucagon are hormones that regulate blood sugar. Which of the following is true? (10.3) K/U
   (a) Insulin and glucagon both follow negative feedback systems.
   (b) Insulin uses negative feedback; glucagon uses positive feedback.
   (c) Insulin uses positive feedback; glucagon uses negative feedback.
   (d) Insulin and glucagon both follow positive feedback systems.
9. What is the function of anabolic steroids? (10.5) K/U
   (a) They reduce muscle mass and strength.
   (b) They increase muscle mass and strength.
   (c) They increase red blood cells that carry more oxygen.
   (d) They decrease red blood cells that carry more oxygen.
10. What is oogenesis? (10.7) K/U
    (a) gland responsible for the production of sex hormones
    (b) term used to describe the end of a female's reproductive capabilities
    (c) production of eggs in the ovaries
    (d) process by which sperm is produced in the testes

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. The main function of the endocrine system is to protect the body. (10.1) K/U
12. Hormones are released only into the bloodstream. (10.1) K/U
13. Adrenocorticotropic hormone (ACTH) is released by the adrenal glands to control the pituitary gland. (10.2) K/U
14. Hyposecretion of growth hormone (hGH) during childhood can result in gigantism. (10.2) K/U
15. Prolactin stimulates the development and secretion of breast milk. (10.2) K/U
16. Glucagon is an example of a glucocorticoid. (10.3) K/U
17. Glucagon and insulin are both produced in the pancreas. (10.3) K/U
18. Many young athletes want to add muscle mass to their bodies. The fast, but dangerous, way of doing this is to take anabolic steroids. (10.5) K/U
19. Anabolic steroids have a variety of well-known negative side effects. (10.5) K/U
20. Males produce sperm constantly, at a rate of 130 million sperm per hour. (10.7) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 10 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which statement about steroid hormones is correct? (10.1) K/U
   (a) They are very soluble in blood.
   (b) They are derived from cholesterol.
   (c) They are hydrophilic.
   (d) They are composed of amino acids.
2. Which statement about protein hormones is correct? (10.1) K/U
   (a) They are lipid based.
   (b) They pass easily through the cell membrane.
   (c) They bind to receptor molecules in the cell membrane.
   (d) none of the above
3. Which statement about steroid hormones is incorrect? (10.1) K/U
   (a) Steroid hormones are made of cholesterol.
   (b) Steroid hormones bind to the target cell's DNA.
   (c) Steroid hormones bind to receptors on their target's cell membrane.
   (d) Steroid hormones enter cells by diffusing through cell membranes.
4. Which endocrine gland is part of the nervous system? (10.2) K/U
   (a) hypothalamus
   (b) pituitary
   (c) adrenal
   (d) thyroid
5. How do the hypothalamus and the pituitary gland work together? (10.2) K/U
   (a) The pituitary produces growth hormone–releasing hormone, which causes the hypothalamus to produce growth hormone.
   (b) The hypothalamus produces growth hormone–releasing hormone, which causes the pituitary to produce growth hormone.
   (c) The hypothalamus produces estrogen, which causes the pituitary to produce progesterone.
   (d) The hypothalamus produces growth hormone–releasing hormone, which causes the pituitary to produce antidiuretic hormone.
6. Where is the thyroid gland located? (10.2) K/U
   (a) on top of the kidneys
   (b) below the stomach, near the liver
   (c) in the pelvic cavity
   (d) in the front of the throat
7. Which gland is correctly paired with the hormone it produces? (10.2) K/U
   (a) ovaries—glucagon
   (b) pancreas—growth hormone
   (c) adrenal glands—epinephrine
   (d) pituitary—aldosterone
8. Which sequence is correct? (10.3) K/U
   (a) beta cells → insulin → decreases blood glucose
   (b) alpha cells → insulin→ increases blood glucose
   (c) beta cells → glucagon → increases blood glucose
   (d) alpha cells → glucagon → decreases blood glucose
9. Which gland secretes glucocorticoids? (10.3) K/U
   (a) pancreas
   (b) adrenal
   (c) thyroid
   (d) hypothalamus
10. Frederick Banting and Charles Best studied dogs in which the pancreas had been surgically removed. Which symptom did they observe? (10.4) K/U
    (a) rise in blood glucose
    (b) unusual thirst
    (c) production of copious amounts of urine
    (d) all of the above
11. Which statement about natural steroid hormones is correct? (10.5) K/U
    (a) One group of natural steroid hormones is anabolic steroids.
    (b) Natural steroid hormones are part of an important treatment for transplant patients.
    (c) Natural steroid hormones are illegal.
    (d) Testosterone and aldosterone are natural steroid hormones.
12. Anabolic steroids are drugs that mimic specific hormones in the body. The more an athlete uses anabolic steroids, the less natural hormone the body produces. Which of the following statements best describes this effect? (10.5) K/U
    (a) conditioned response
    (b) osmoregulatory response
    (c) form of positive feedback
    (d) form of negative feedback

13. What does erythropoietin (EPO) do? (10.5) K/U
    - (a) It increases muscle mass and strength.
    - (b) It decreases fat and improves muscle mass.
    - (c) It increases red blood cells that carry more oxygen.
    - (d) It makes steroids difficult to detect.
14. What is the general term for the male sex hormones? (10.7) K/U
    - (a) estrogens
    - (b) thymosins
    - (c) androgens
    - (d) prostaglandins
15. Which hormone stimulates the beginning of the ovarian cycle? (10.7) K/U
    - (a) gonadotropin-releasing hormone
    - (b) estrogen
    - (c) follicle-stimulating hormone
    - (d) luteinizing hormone

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

16. Protein hormones consist of amino acid chains, which range in length from 3 amino acids to more than 200 amino acids. (10.1) K/U
17. Protein hormones have an affinity for water and diffuse well through the blood and intercellular fluids. (10.1) K/U
18. Neurohormones are produced by neurons in the hippocampus. (10.2) K/U
19. Thyroid hormones lower the levels of K^+ ions in the blood, thus inhibiting the ongoing release of calcium from bone. (10.2) K/U
20. Type 1 diabetes is caused by an inability to produce insulin due to a failure of the beta cells in the islets of Langerhans. (10.3) K/U
21. Treatment of diabetes requires constant monitoring of the blood calcium level. (10.3) K/U
22. Frederick Banting and Charles Best knew from the work of earlier scientists that a healthy dog would contract diabetes if its thyroid was removed. (10.4) K/U
23. Long-term use of synthetic steroids can lead to baldness, shrinking testes, irregular reproductive cycles, and many other physical and psychological side effects. (10.5) K/U
24. Natural steroid hormones in the human body control both male and female sexual development and reproduction, the adrenal fight-or-flight response, and the level of blood glucose. (10.5) K/U
25. Reproduction is controlled by sex hormones, which are primarily produced in the adrenal glands. (10.7) K/U
26. Spermatogenesis is controlled by the male androgen hormone aldosterone. (10.7) K/U

Match each term on the left with the most appropriate description on the right.

27. (a) insulin
    - (b) oxytocin
    - (c) thyroxin
    - (d) calcitonin
    - (e) growth hormone
    - (f) adrenocorticotropic hormone (ACTH)

    - (i) increases fatty acid metabolism and amino acid uptake by the body
    - (ii) regulates the metabolism of the body
    - (iii) stimulates the adrenal cortex
    - (iv) causes the uterus to contract for birth and the breasts to lactate
    - (v) speeds up the removal of sugar from the bloodstream
    - (vi) lowers Ca^{2+} levels in the blood (10.2, 10.7) K/U

28. (a) chorionic gonadotropin
    - (b) testosterone
    - (c) progestins
    - (d) spermatogenesis
    - (e) menstrual cycle
    - (f) gonads

    - (i) predominantly female sex hormones, including progesterone
    - (ii) glands responsible for the production of sex hormones, as well as egg and sperm cells
    - (iii) monthly cycle of events in sexually mature females that prepares the uterus for the implantation of an egg
    - (iv) principal androgen
    - (v) process by which sperm cells are produced in the testes from precursor cells
    - (vi) hormone in blood or urine that is the basis of pregnancy tests (10.7) K/U

Write a short answer to each question.

29. Give examples of how an endocrine gland differs from an exocrine gland. (10.1) K/U
30. (a) What are the two methods in which hormones bind to receptor cells?
    - (b) How is the method of binding determined? (10.1) K/U
31. (a) Identify the gland in the human body that requires iodine to function properly, and explain why.
    - (b) If there is not enough iodine in the diet, what happens to this gland? (10.2) K/U

32. Which group of hormones of the adrenal glands regulates the metabolism of carbohydrates, proteins, and fats? (10.2) K/U

33. Explain the relationship between the secretion of parathyroid hormone and each of the following: (10.2) K/U
    (a) calcium level in the blood
    (b) calcium absorption

34. (a) Where is the pineal gland located?
    (b) What is its function? (10.2) K/U

35. List four hormones that are involved in controlling the rate at which sugar is broken down (catabolized). (10.3) K/U

36. Describe the symptoms of hyperglycemia. (10.3) K/U

37. (a) What is gestational diabetes?
    (b) How does it differ from type 1 and type 2 diabetes? (10.3) K/U

38. Is testosterone a natural hormone or a synthetic hormone? Explain your answer. (10.5) K/U

39. What is a masking agent? (10.5) K/U

40. Explain the difference between an ovum and a zygote. (10.7) K/U

Understanding

41. What components make up the endocrine system? (10.1) K/U

42. Explain the significance of insect juvenile hormone, in terms of its role in an organism. (10.2) K/U

43. Identify the major hormones of the anterior pituitary gland, and list their target organs or tissues. (10.2) K/U

44. Create your own chart, table, or diagram to list the various hormones of the endocrine system and summarize where they come from, how they act, and how they affect the body. (10.2) K/U C

45. Epinephrine is released into the bloodstream when the body is stressed. List four effects that epinephrine may have on the body once it has been released into the bloodstream. (10.3) K/U

46. Explain how parathyroid hormone (PTH) and calcitonin assist in blood ion regulation. (10.3) K/U

47. Describe how the hypothalamus and the pituitary gland work together. (10.3) K/U

48. Select the letter in **Figure 1** that best describes each statement below. Record your answers in your notebook. You may need to use some letters more than once. (10.1, 10.2, 10.3, 10.7) K/U

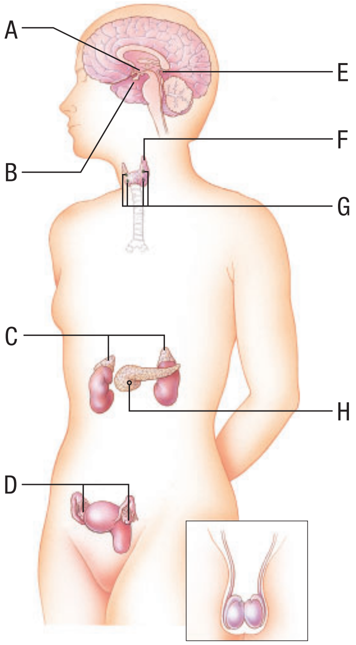


Figure 1

    (a) gland that produces and releases insulin
    (b) gland that is responsible for primary calcium regulation
    (c) gland that controls biological rhythms
    (d) glands that produce hormones that, in turn, stimulate other glands to produce hormones
    (e) gland that produces progesterone and is regulated by GnRH
    (f) production site of the hormone that is involved in milk production
    (g) production site of the hormone that controls water balance by increasing the permeability of nephrons to water
    (h) site from which oxytocin is released

49. Secondary sexual characteristics develop in both genders after puberty. (10.7) K/U
    (a) List three secondary sexual characteristics for males.
    (b) List three secondary sexual characteristics for females.
    (c) Which hormone controls the development of secondary sexual characteristics?

Analysis and Application

50. Hormone A binds to intracellular receptors in a tissue and, as a result, the tissue is now sensitive (or responsive) to hormone B. Explain what has happened. (10.1) K/U T/I

51. Hormones are classified as either protein or steroid. They are also classified as tropic or non-tropic. Compare and contrast tropic and non-tropic hormones. (10.1) K/U T/I

52. (a) The endocrine system is considered to be an integrative system in the body. Explain why.
    (b) What other body system would also be considered integrative? (10.1) K/U T/I A

53. The pituitary gland has been referred to as the "master gland." Write a brief paragraph to explain why you agree or disagree with this analogy. (10.2) K/U T/I C

54. The blood glucose levels of four people were followed over time. Three of the people ate a meal. The results are shown in the graphs in **Figure 2**. Use Figure 2 to answer the following questions and explain your answer for each. (10.3) K/U T/I A

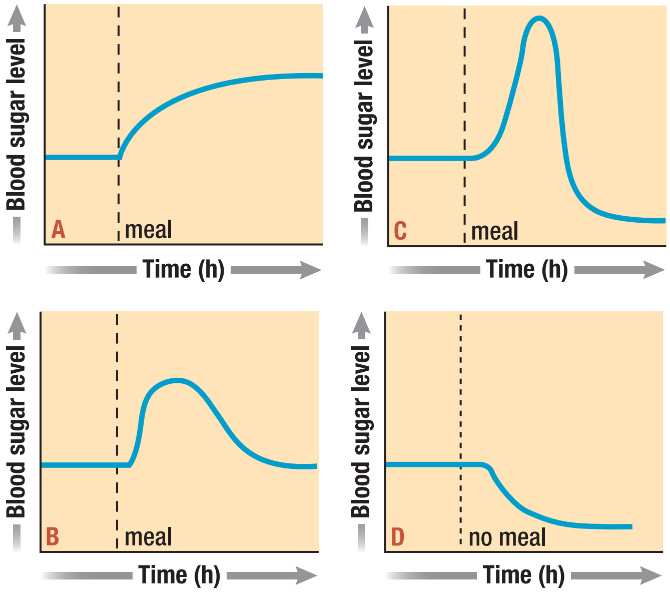


Figure 2

    (a) Which graph shows the results for someone who is suffering from diabetes mellitus? Explain your answer.
    (b) Which graph shows the results for someone who has too little glucagon? Explain your answer.
    (c) Which graph shows the results for someone who has a normally functioning pancreas? Explain your answer.

55. Diabetes is a disease that can be controlled if certain measures are taken. (10.3) K/U T/I
    (a) Explain why most people with diabetes must reduce the amount of carbohydrates they consume.
    (b) What potential complications do diabetics face if they do not control their diabetes?

56. Suppose that you are doing an experiment to gain a better understanding of the effects of pancreatic radiation on the blood glucose level of lab mice. You do the following:
    - expose two mice to radiation for 50 min, measuring their blood glucose level every 10 min
    - test the blood glucose level of a lab mouse that did not receive any radiation over the same time periods
    - collect the data in **Table 1** (10.3) K/U T/I C

Table 1 Blood Glucose Level (BGL) of Mice (g/100mL)

	Exposure to radiation (min)					
Blood glucose level	**0**	**10**	**20**	**30**	**40**	**50**
young male mouse exposed to radiation (g/100 mL)	0.09	0.18	0.23	0.28	0.28	0.28
old female mouse exposed to radiation (g/100 mL)	0.13	0.17	0.22	0.27	0.32	0.33
young female mouse not exposed to radiation (g/100mL)	0.09	0.10	0.09	0.08	0.09	0.10

    (a) Suggest a hypothesis for this experiment.
    (b) What variables were being tested?
    (c) Based on the information available, what variables do you think were controlled?
    (d) Describe any trends you observe in the data.
    (e) Create an appropriate graph to best report the data.
    (f) What conclusion can you draw from the data?
    (g) Based on the results, what effect do you think radiation might have on the pancreas?
    (h) What could be done to make this experiment more valid? Explain.

57. During pregnancy, the placenta produces progesterone. Is this an advantage or a disadvantage for women? Explain your reasoning. (10.7) K/U

58. **Figure 3** shows a graph of the rate of glucose absorption in the small intestine over time. The solid line shows the rate when thyroxine in the blood is high, and the dotted line shows the rate when thyroxine in the blood is low. Based on the graph, what conclusion can you draw about glucose absorption and thyroxine? (10.2, 10.3) K/U T/I

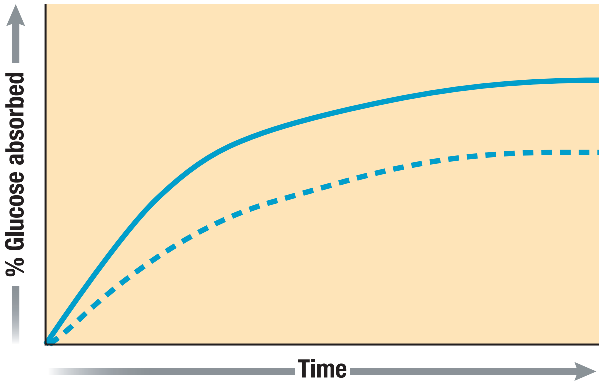


Figure 3

Evaluation

59. If a hormone is hydrophobic and binds to membrane receptors, what type of molecule is the hormone most likely to be? Explain your answer. (10.1, 10.2) K/U T/I
60. Explain why some individual hormones have multiple effects on different target tissues. (10.1, 10.2) K/U T/I
61. A patient complains to a doctor about having the following symptoms:
    - diminished hearing
    - cold intolerance
    - fatigue
    - lethargy
    - constipation

    The doctor orders several tests and receives these results:
    - weight gain
    - elevated TSH
    - T_4 decrease
    - hypoglycemia

    Use what you have learned about the endocrine system in this chapter to answer the following questions:
    (a) What endocrine glands do you think may be involved in causing the patient's symptoms?
    (b) What disorder might the doctor suspect, based on the symptoms and the test results?
    (c) What possible treatments would you suggest for this disorder? (10.2) K/U T/I A
62. In the past, people who lived near an ocean rarely suffered from goiter. The farther inland people lived, the more common the disorder was. Today, goiter is rarely seen, even in people who do not eat seafood. Provide a possible explanation for this observation. (10.2) K/U T/I
63. Many overweight people suffer from thyroid hormone deficiency. Explain how this deficiency can result in the excess storage of fat. (10.2) K/U T/I
64. A blood glucose test can be ordered to measure the amount of glucose in the blood. This test can also be used to detect hyperglycemia and hypoglycemia, to help diagnose diabetes, and to monitor the glucose level of someone who has diabetes. The blood glucose level can be measured in three different ways: after an 8 to 10 h fast, randomly, or after a meal.

    A patient receives all three tests during one day. Explain what differences you would expect to see in the results of the tests. (10.3) K/U T/I C
65. In 1923, the Nobel Committee awarded Frederick Banting and John Macleod the Nobel Prize in Physiology or Medicine. The decision of the Nobel Committee angered Banting because he felt that the prize should have been shared by him and Charles Best, rather than by him and Macleod. To give credit to Best, Banting shared his cash award with him. Macleod shared his cash award with James Collip. (10.4) T/I C
    (a) The 1923 Nobel Prize in Physiology or Medicine for the discovery of insulin has been much debated. Who do you think should have received the award? Justify your position.
    (b) Banting and his team gave the patent rights for insulin to the University of Toronto to help fund future research. Do you think this was a good move? Would it have been better for them to have kept the patent or sold it to a pharmaceutical company, instead of giving it away? Explain your reasoning.

Reflect on Your Learning

66. Consider what you have learned about the endocrine and reproductive systems and how your understanding has changed as a result. Create a three-column KLN chart with the following headings: What I Knew, What I Learned, and What I Still Want/Need to Know. In the first column, summarize what you knew before you started this chapter. In the second column, list or describe the new knowledge you have gained. In the third column, make a list of questions you would still like to have answered. K/U T/I C A

67. A recent article in the *London Daily Mail Online* newspaper claims that British and American athletes are competing at a disadvantage because their national drug-policing regimes are much more intense than those of some other countries. In response, the chief executive of the U.S. Anti-Doping Agency claims that the performances of athletes from Jamaica, Russia, and Spain are compromised because drug testing in those countries is not stringent enough and does not involve out-of-competition and no-notice testing, or tests for EPO and human growth hormone. T/I C A
   (a) Do you think it is fair to expect all countries to have the same drug-testing standards? Explain why or why not.
   (b) What factors might affect the level of drug testing in each country?
   (c) Some people have suggested that it is impossible to ensure that all athletes are free from performance-enhancing drugs. Do you think it is worth considering two levels of sport competition: drug-free games and drug-enhanced games? Justify your response.
   (d) Drug testing in Canada normally begins at the elite Canada Games level. At what stage do you think drug testing should begin? Explain your reasoning.
   (e) What are the pros and cons of drug testing below the elite level of sports?

68. According to the Canadian Diabetes Association, 90 % of Canadians believe that diabetes is stressing our health-care system. Many people believe that diabetes is at epidemic proportions in North America and that this will have an impact on future generations. They have suggested that our dietary habits need to change and we need to become more active. T/I C
   (a) Are you concerned that you could possibly have to deal with diabetes in the future?
   (b) What lifestyle changes, if any, do you think would benefit Canadians as a whole? Explain your reasoning.
   (c) What lifestyle changes, if any, do you think would benefit you as an individual? Explain your reasoning.

WEB LINK

Research

69. Addison's disease and Cushing's syndrome are both diseases of the endocrine system. They are both caused by problems with secretion levels of adrenocorticotropic hormone (ACTH) from the anterior pituitary. However, these are the only two similarities between the diseases. Using the Internet and other sources, find out more about the differences between Addison's disease and Cushing's syndrome. Write a short report to summarize your findings. T/I C A

70. In this chapter, you read about type 1 and type 2 diabetes mellitus, as well as gestational diabetes. There is another type of diabetes, called diabetes insipidus, that is less common. Use the Internet and other sources to research this disease. Create a brief report that includes the following information:
   - causes and risk factors
   - signs and symptoms
   - treatment
   - differences between diabetes mellitus and diabetes insipidus K/U T/I C

71. Use the Internet and other sources to research two endocrine system disorders: dwarfism and gigantism. Produce a visual or audiovisual presentation to share your findings. Consider the following questions when preparing your presentation:
   - What is gigantism? What is dwarfism?
   - What are the signs and symptoms of gigantism?
   - How does gigantism differ from acromegaly?
   - What are the treatment and prognosis for gigantism?
   - What are the possible complications of gigantism?
   - What types of dwarfism exist, and how are they different?
   - What are the signs and symptoms of dwarfism?
   - What are the treatment and prognosis for dwarfism?
   - What are the possible complications of dwarfism?

   T/I C

72. The term "stress" was originally used by an endocrinologist, Hans Selye, in the 1930s to describe physiological responses in lab animals. He found that they had similar reactions to what he described as the three stages of the General Adaption Syndrome (GAS): reaction, resistance, and exhaustion. Selye later broadened and popularized the term to include the perceptions and responses of humans who are trying to adapt to the challenges of everyday life. Used broadly, stress ranges from mild irritations to severe problems that result in health issues. In popular usage, stress includes almost any event or situation between these two extremes. Signs of stress can be cognitive, emotional, physical, or behavioural.

   Conduct online research to learn about Selye's stress model. Then create a pamphlet or poster to help your classmates better understand the effects of stress on the body. Your pamphlet should include the following information:
   - descriptions of the three stages of GAS
   - hormones that are involved in the facilitation of stress
   - possible long-term effects of chronic stress
   - ways to reduce stress in your life T/I C A

CHAPTER 11 The Nervous System

KEY CONCEPTS

After completing this chapter you will be able to

- describe how the nervous system detects many sensory inputs and coordinates many of the body's responses
- understand that neurons are specialized nerve cells that communicate with each other through an electrochemical process
- explain how neurotransmitters allow the transmission of electrochemical signals across a synapse from one nerve cell to another
- understand how the components of the central nervous system (the brain and spinal cord) work in tandem to relay and process messages in the body
- understand how the peripheral nervous system and its divisions, including the autonomic nervous system, maintain homeostasis in the body
- understand how the nervous, endocrine, and excretory systems interact as they respond to stress and maintain homeostasis

How Does the Nervous System Contribute to Homeostasis?

The human brain is the control centre of the body. If something goes wrong with the brain, other parts of the body will likely be affected. The nervous system is the body's interface with the external environment and the control system that manages the internal environment. Although the brain and spinal cord are surrounded by strong bones, they are still susceptible to injuries from severe impacts. How could such injuries affect the ability of the nervous system to maintain homeostasis?

Hockey superstar Sidney Crosby has been called "the best player in the game" by Wayne Gretzky. On January 1, 2011, Crosby crumpled to the ice after a collision in which he was struck in the head. A few days later, he received another crushing check that caused his head to slam into the boards. Crosby was diagnosed with concussion: a brain injury defined by medical professionals as "a complex pathophysiological process affecting the brain, induced by biomechanical forces." A concussion is caused by a direct blow to the head or a blow elsewhere on the body in which the force is transmitted to the head. Crosby became one of nearly 50 NHL players who were taken out of the 2010–2011 season lineup due to concussion.

The brain can be damaged by a variety of factors including physical trauma, physiological problems (such as a stroke or tumour), prolonged oxygen deprivation, infections (such as meningitis), and poisoning by heavy metals such as mercury. Like all body tissues, brain tissue cannot function properly when damaged, and the consequences of damage can vary significantly in character and severity. Brain damage from physical injuries and strokes can be localized, affecting only a small area of the brain. Brain damage caused by other factors, such as poisoning or disease, is generalized and affects the whole brain.

Depending on which areas of the brain are damaged, the symptoms may be physical (for example, changes in vision, hearing, smell, or sense of touch; poor muscle coordination; paralysis; tremors; or slurred speech), cognitive (for example, the inability to understand speech, express thoughts, think logically, and remember), or physiological (for example, a reduced ability of the body to regulate internal functions). Behavioural and personality changes are also common after traumatic brain injuries.

In this chapter, you will examine the brain and other structures of the nervous system and learn how these structures function to maintain a stable internal environment. You will also explore how the body responds to external and internal stresses that tend to disrupt homeostasis.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Why and how do you think a concussion might affect the nervous system and other systems in the human body?
2. Do you think it is possible that an individual could have brain damage without being aware of it? Explain.
3. How might brain damage affect homeostasis?
4. What other problems of the nervous system might threaten homeostasis or the survival of an organism?

Mini Investigation

Cold Sensations

Skills: Performing, Observing, Analyzing, Communicating

SKILLS HANDBOOK A2.1

Some people participate in "polar bear swims," or winter swims in very cold water (**Figure 1**). What was the coldest water you ever swam in? How did it feel? How long did you stay in the water? In this activity, you will compare how long your hand and your elbow can tolerate ice-cold water.

Figure 1 People participating in a "polar bear swim"

Equipment and Materials: large beaker or bowl; stopwatch; ice; water; paper towels

If you have a medical problem that might make it unsafe for you to participate in this experiment, please inform your teacher.

1. Predict which part of your arm—your hand or your elbow—will have greater sensitivity to ice-cold water. Explain your prediction.
2. With a partner, create a numerical coding system that you can use to rate the levels of physical discomfort.
3. Put water and ice in the beaker or bowl.
4. Determine how long you can tolerate your (a) hand and (b) elbow in the ice-cold water. Ensure that you remove your hand or elbow before it becomes too painful. Your partner will time you. Record the times.
5. Change roles with your partner, and repeat Step 4.

A. Was your prediction correct? T/I

B. What sensation did you experience when you first placed your hand in the water? Did it change over time? T/I

C. Based on your current knowledge of the nervous system, explain what happens when you immerse your hand or elbow in ice-cold water. K/U T/I

D. Use your observations to propose a hypothesis about the distribution of cold sensory receptors in different parts of the body. Summarize your hypothesis in one paragraph. T/I C

11.1 The Role of the Nervous System

How do organisms make sense of their environment? The flow and processing of information from the environment is astounding, even in relatively simple animals such as bees. The complex nervous system and (to a lesser extent) endocrine system of bees mediate specific behaviours triggered by information from the environment. For example, bees are able to find food and communicate with other bees to share information about the location of food.

Bees do not see colours in the same way that humans do. They see a broader spectrum of light, including ultraviolet light. Bees are primarily attracted to flowers based on the visual characteristics of the flowers. They are particularly attracted to flowers that radiate more ultraviolet light, such as white, bright yellow, blue, or purple flowers (**Figure 1**). Odour is a secondary stimulus, which supplements the visual cues and enables bees to zero in on their floral targets. After collecting nectar and pollen, bees need to navigate back to their hive. They use the Sun as a navigational aid, as well as Earth's magnetic field. They also rely on visual landmarks for orientation.

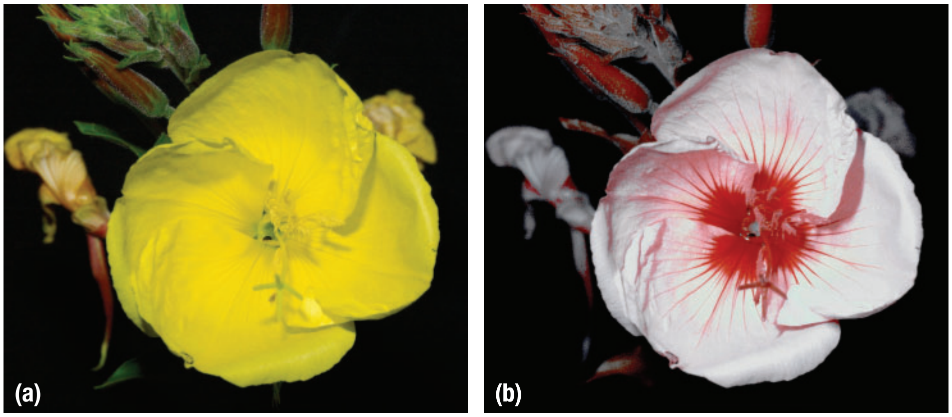


Figure 1 (a) The human eye sees this flower as yellow. (b) A photograph taken with a special filter allows us to see the flower as a bee sees it. Notice the patterns that radiate out from the pollen-producing structure in the centre.

In this section, you will examine the structures of the nervous system and the processes that enable an organism to sense and respond to its external environment and control its internal environment.

neuron a nerve cell that is capable of conducting nerve impulses

neural signalling the reception, transmission, and integration of nerve impulses by neurons, and the response to these impulses

afferent neuron a neuron that carries impulses from sensory receptors to the central nervous system; also called a sensory neuron

interneuron a local circuit neuron of the central nervous system that relays impulses between afferent (sensory) and efferent (motor) neurons

efferent neuron a neuron that carries impulses from the central nervous system to skeletal muscles; also known as a motor neuron

Neural Signalling

A **neuron** is a specialized nerve cell that is the functional unit of the nervous system. It allows an organism to receive and respond to both internal and external stimuli. **Neural signalling**—communication by neurons—is the process by which an animal responds appropriately to stimuli. In most animals, the four components of neural signalling are reception, transmission, integration, and response. Reception is the detection of a stimulus. It is performed by neurons and by specialized sensory receptors, such as those in the eyes and skin. Transmission is the movement of a message along a neuron to either another neuron or a muscle or gland. Integration is the sorting and interpretation of multiple neural messages and the determination of the appropriate response. Response is the output or action resulting from the integration of neural messages.

Neural signalling involves three functional classes of neurons (**Figure 2**, next page). **Afferent neurons** (also called sensory neurons) transmit stimuli collected by their sensory receptors to **interneurons**, which integrate the information to formulate an appropriate response. Interneurons are found primarily in the brain and spinal cord. In humans and some other primates, about 99 % of the neurons are interneurons. **Efferent neurons** carry the response signal away from the interneurons to the effectors, which are the muscles and glands. Efferent neurons that carry signals to skeletal muscles are called motor neurons. The information-processing steps in the nervous system can be summarized as (1) stimulus reception by sensory receptors on afferent neurons; (2) message transmission by afferent neurons to interneurons; (3) integration of neural messages in interneurons; (4) response by the transmission of neural messages by efferent neurons to effectors, where appropriate action occurs.

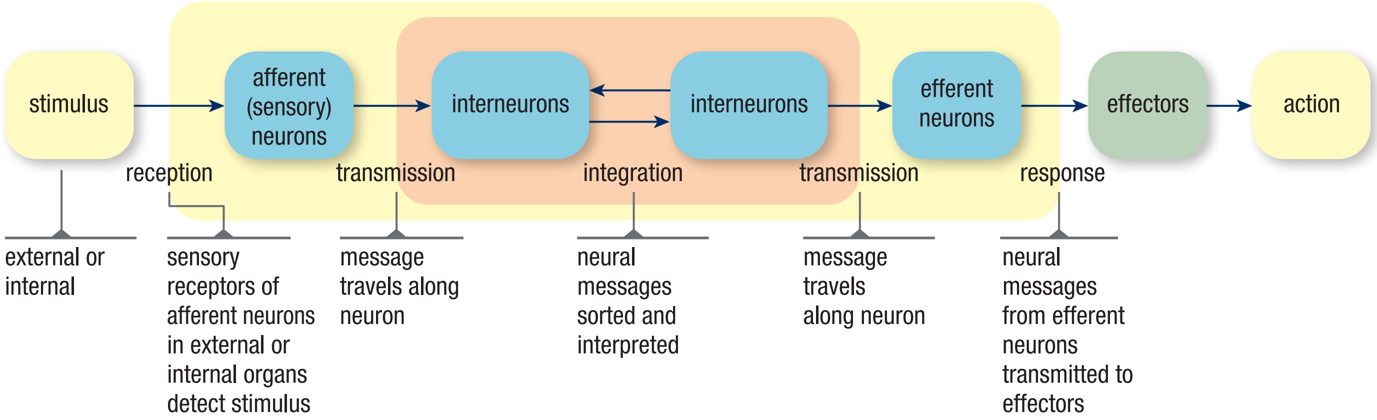

stimulus
afferent (sensory) neurons
interneurons
interneurons
efferent neurons
effectors
action
reception
transmission
integration
transmission
response
external or internal
sensory receptors of afferent neurons in external or internal organs detect stimulus
message travels along neuron
neural messages sorted and interpreted
message travels along neuron
neural messages from efferent neurons transmitted to effectors

Figure 2 Neural signalling: information-processing steps in the nervous system following an external (e.g., light) or internal (e.g., change in blood pressure or body temperature) stimulus

Neurons vary widely in shape and size. However, all neurons have an enlarged cell body and two types of extensions or processes (**Figure 3**). The cell body, which contains the nucleus and most of the organelles in the cell, synthesizes most of the neuron's proteins, carbohydrates, and lipids. Specialized projections from the cell body conduct electrical signals, which are produced by ions flowing down concentration gradients, through channels in the plasma membrane of the neuron. **Dendrites** (from *dendros* meaning "tree") are generally highly branched projections that form a tree-like outgrowth at one end of the neuron. Dendrites receive the signals and transmit them toward the cell body. **Axons** (from *axon* meaning "axis") are specialized projections that conduct signals away from the cell body to another neuron or an effector. Each neuron usually has a single axon that arises from a junction with the cell body called an axon hillock. The axon has branches at its tip that end as small, button-like swellings called axon terminals. The axon terminals are the points of connection that enable the signals to be transmitted from one neuron to another or from a neuron to an effector. The more terminals in contact with a neuron, the greater its capacity to integrate incoming information.

dendrite a projection of cytosol that carries signals toward the nerve cell body

axon an extension of cytosol that carries nerve signals away from the nerve cell body

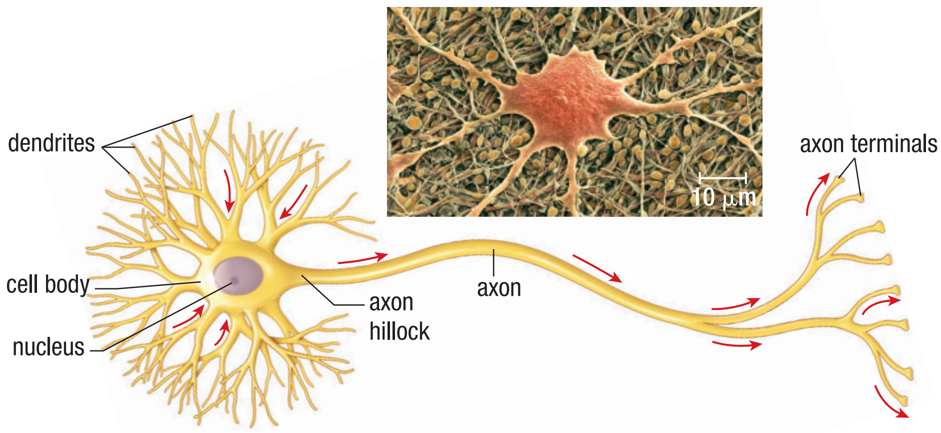


Figure 3 The structure of a neuron (nerve cell). The arrows indicate the direction of the electrical impulse that travels along the neuron. The inset image is a scanning electron micrograph of a motor neuron.

Axons are often very long and extremely thin projections from the cell body. Usually, many axons are bundled together to form nerve fibres of various sizes, commonly referred to simply as "nerves" (**Figure 4**). These nerves branch extensively to relay signals throughout the periphery of the entire body.

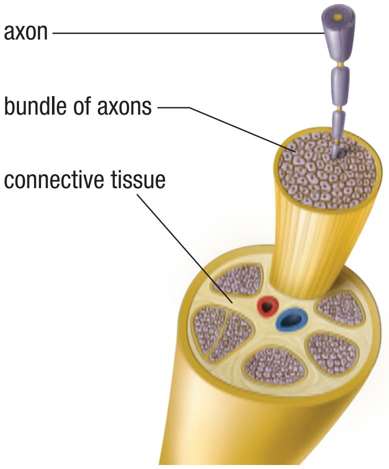


Figure 4 Axons are bundled together to form nerve fibres similar to the way small fibres are bundled together to form a fibre-optic telephone cable.

Connections between the axon terminals of one neuron and the dendrites or cell body of a second neuron form the basic elements of a neuronal circuit. A typical neuronal circuit contains an afferent neuron, one or more interneurons, and an efferent neuron. Interneurons may receive input from several axons and may, in turn, connect to other interneurons and several efferent neurons. In this way, circuits of neurons combine into networks that interconnect the different parts of the nervous system.

Neuron Support System

glial cell a non-conducting cell that is important for the structural support and metabolism of nerve cells

myelin sheath an insulated covering over the axon of a nerve cell

node of Ranvier a regularly occurring gap between sections of myelin sheath along the axon

Not all cells in the nervous system are neurons. **Glial cells** do not conduct electrical signals, but provide nutrition and support to neurons. One type of glial cells, called Schwann cells, form tightly wrapped layers of plasma membrane, called **myelin sheaths**, around axons (**Figure 5**). These myelin sheaths act as electrical insulators due to their high lipid content. The gaps between Schwann cells, called **nodes of Ranvier**, expose the axon membrane directly to extracellular fluids. This arrangement of insulated stretches of axons, punctuated by uninsulated gaps, speeds the rate at which electrical impulses move along the axons.

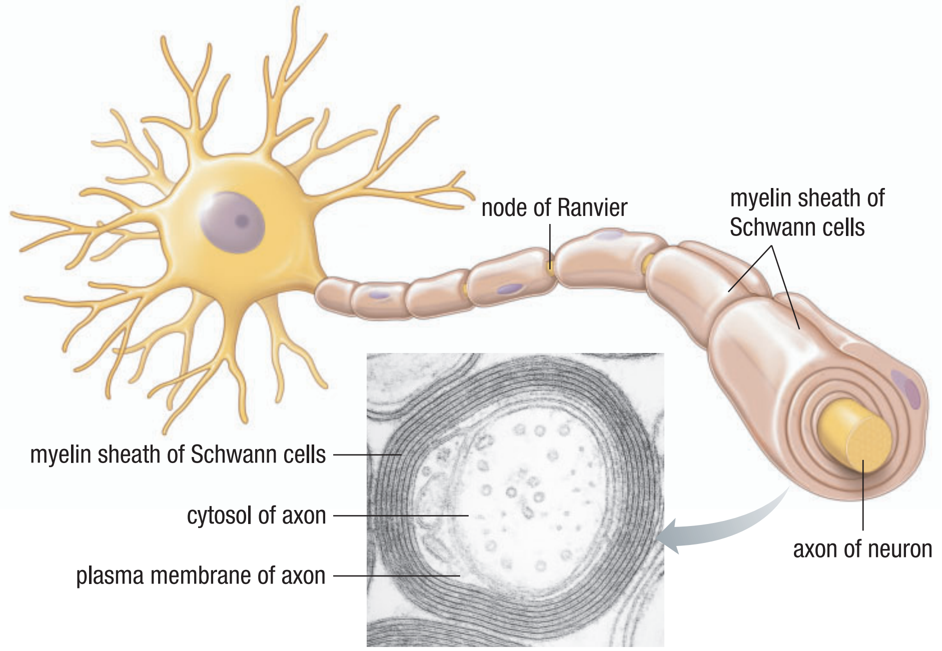


Figure 5 The myelin sheath formed by Schwann cells acts like an electrical insulator. As many as 300 overlapping layers of Schwann cell plasma membrane wind around an axon, like a jelly roll.

Unlike most neurons, glial cells retain the capacity to divide throughout the life of an animal. This capacity allows glial tissues to replace damaged or dead cells. However, it also makes them the source of nearly all brain tumours, which are produced when regulation of glial cell division is lost.

The Structure and Organization of the Human Nervous System

central nervous system (CNS) the body's coordinating centre for mechanical and chemical actions; made up of the brain and spinal cord

peripheral nervous system (PNS) all parts of the nervous system, excluding the brain and spinal cord; relays information between the central nervous system and other parts of the body

The nervous system of most invertebrates and vertebrates, including humans, is made up of two functional subsystems. Interneurons form the **central nervous system (CNS)**, which consists of the brain and spinal cord. The **peripheral nervous system (PNS)** is the subsystem that communicates with the central nervous system. The PNS can be further divided into the **afferent system** (which receives input through receptors and transmits it to the CNS) and the **efferent system** (which carries signals to the muscles and glands that are effectors). "Afferent" refers to carrying *toward*, and "efferent" refers to carrying *away*.

The nervous system is really a system of systems and subsystems that is similar to the collection of neighbourhoods in a large city and the transportation systems that connect these neighbourhoods. A schematic representation of the entire system, including both the CNS and PNS, is illustrated in **Figure 6**. The CNS and PNS will be explored in detail in Sections 11.3 and 11.4.

afferent system the component of the peripheral nervous system that receives input through receptors and transmits the input to the central nervous system

efferent system the component of the peripheral nervous system that carries signals away to the effectors (muscles and glands)

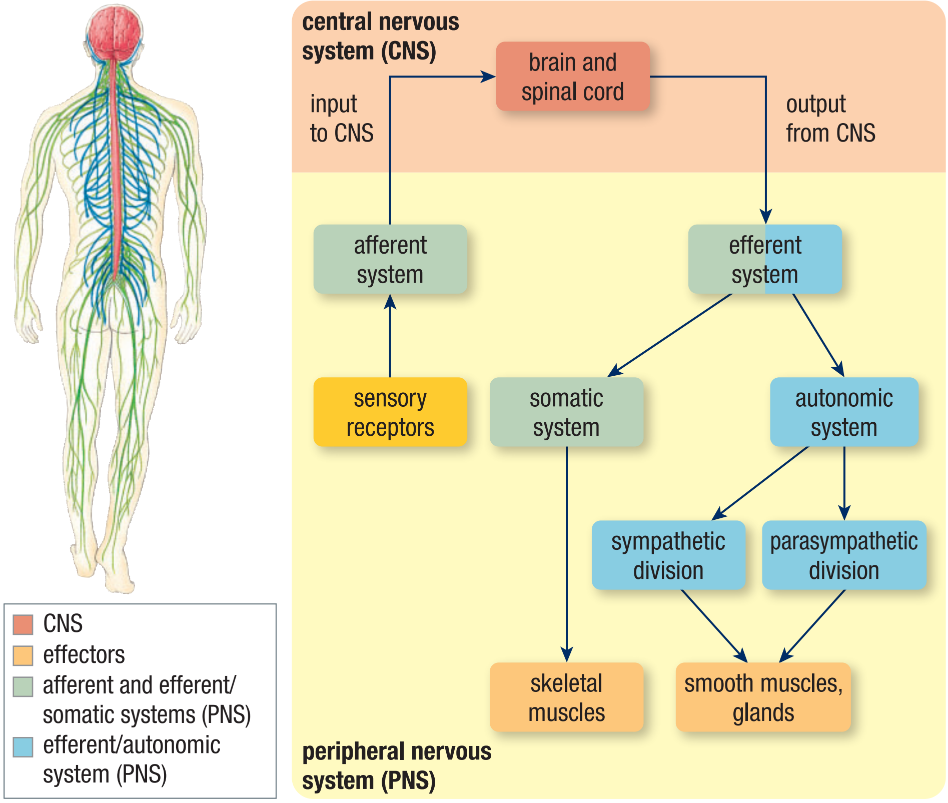


Figure 6 Overview of the human nervous system, comprising the central and peripheral nervous systems (CNS and PNS)

The efferent system is subdivided into the **somatic system** (which communicates with the skeletal muscles) and the **autonomic system** (which communicates with smooth muscles and glands). The somatic system is essentially voluntary, although some contractions of skeletal muscles (reflexes, shivering, and muscle contractions that maintain posture and balance) are unconscious and involuntary. The autonomic system controls mainly involuntary processes, such as digestion, secretion by sweat glands, circulation of the blood, and contraction of smooth muscles in all parts of the body.

The autonomic system is further subdivided into two divisions: the sympathetic division and the parasympathetic division. These divisions are always active and have opposing effects on the organs that they affect, thereby enabling precise control. The **sympathetic division** dominates in situations that involve stress, danger, excitement, or strenuous physical activity. Signals from the sympathetic division increase the force and rate of the heartbeat, raise the blood pressure by vasoconstriction, dilate air passages in the lungs, induce sweating, and dilate the pupils. The **parasympathetic division**, in contrast, dominates during quiet, low-stress situations, such as relaxation. Under its influence, the effects of the sympathetic division, such as rapid heartbeat and elevated blood pressure, are reduced, and maintenance activities, such as digestion, predominate.

somatic system a subdivision of the efferent system (within the PNS); composed of efferent (motor) neurons that carry signals to skeletal muscles in response to external stimuli

autonomic system a subdivision of the efferent system (within the PNS); regulates the internal environment

sympathetic division one of two subdivisions of the autonomic nervous system; increases energy consumption and prepares the body for action

parasympathetic division one of two subdivisions of the autonomic nervous system; stimulates body activities that acquire and conserve energy

Investigation **11.1.1**

Testing Learned Responses (p. 554)

You have learned how the nervous system receives information from conditions in the internal and external environment, and responds to those conditions. In this investigation, you will condition an organism to respond differently than usual to external stimuli.

neural circuit the coordination of the receptor, afferent neuron, interneuron, efferent neuron, and effector in response to a stimulus

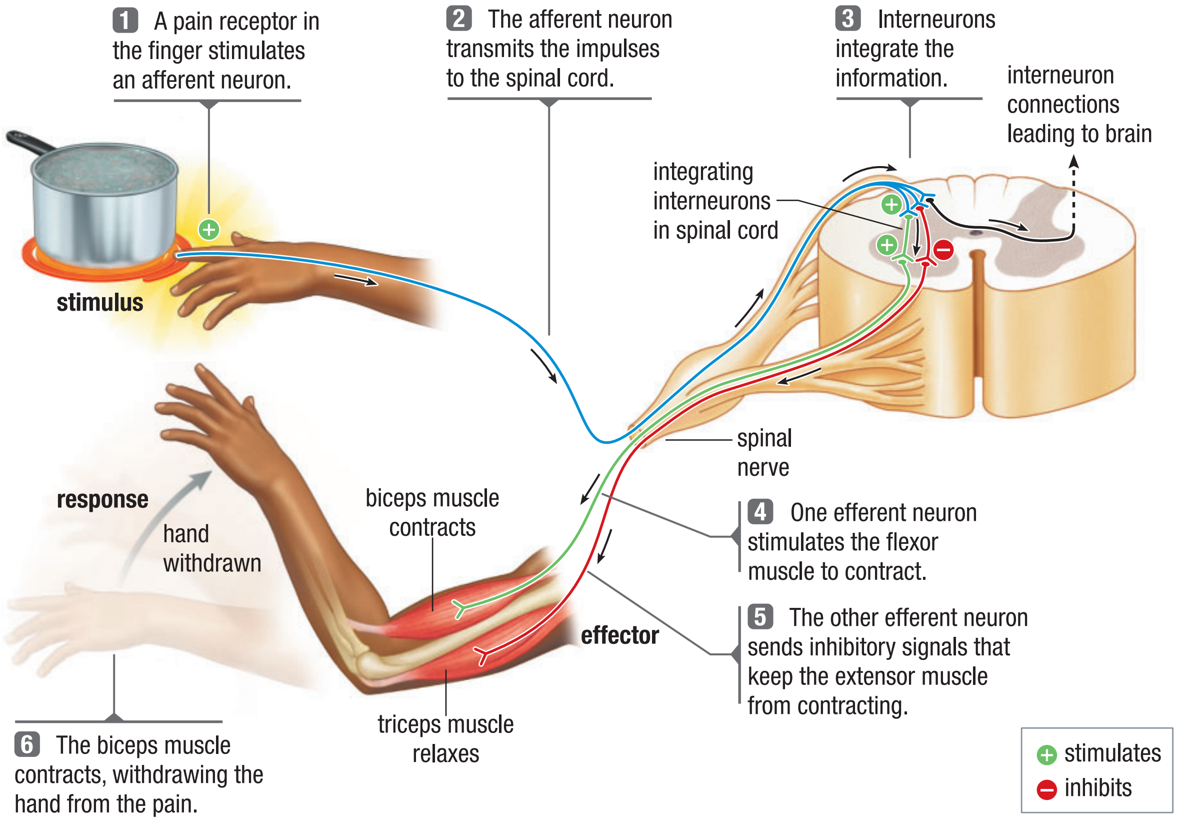
reflex arc a neural circuit that travels through the spinal cord but does not require the coordination of the brain; allows for reflex actions

Neural Circuits and the Reflex Arc

Ouch! When your finger accidentally comes in contact with something very hot, such as the heating element on a stove, your reaction is instantaneous. You do not need to stop and think about what to do—you immediately pull away your finger. Thermal energy is detected by your skin's pain receptors and thermoreceptors, which stimulate an afferent neuron. The afferent neuron transmits the impulse to at least two interneurons in the spinal cord, which, in turn, relay the impulse to an efferent neuron—a motor neuron that coordinates the rapid withdrawal of your hand from the source of the thermal energy, and perhaps an involuntary scream of pain. Such reactions are involuntary and occur in a fraction of a second, without conscious thought. Processing the same information consciously would require too much time and could result in a serious injury.

This situation is an example of a **neural circuit**, which consists of five components: the receptor, the afferent neuron, the interneuron, the efferent neuron, and the effector. The simplest neural circuit is the **reflex arc**. An example of the reflex arc is the withdrawal reflex that results when your finger touches a very hot object (**Figure 7**). A reflex arc is a circuit that does not require the coordinating effort of the brain.

Interneurons connected to the reflex circuits also send signals to the brain, making you aware of the stimulus that caused the reflex. When a reflex movement withdraws your hand from a hot surface or another damaging stimulus, you feel the pain shortly after the hand is withdrawn. This delay in feeling the pain is the extra time required for the impulses to travel from the neurons of the reflex to the brain.



1 A pain receptor in the finger stimulates an afferent neuron.
2 The afferent neuron transmits the impulses to the spinal cord.
3 Interneurons integrate the information.
interneuron connections leading to brain
integrating interneurons in spinal cord
stimulus
spinal nerve
response
hand withdrawn
biceps muscle contracts
4 One efferent neuron stimulates the flexor muscle to contract.
effector
5 The other efferent neuron sends inhibitory signals that keep the extensor muscle from contracting.
triceps muscle relaxes
6 The biceps muscle contracts, withdrawing the hand from the pain.
+ stimulates
− inhibits

Figure 7 The withdrawal reflex is the result of a series of steps that the nervous system uses to integrate incoming information and respond appropriately. It happens so rapidly that the experience of pain occurs after the hand is already withdrawn from the stimulus, such as the hot stove element.

11.1 Review

Summary

- The nervous system of an animal has four main functions: (1) it receives information about conditions in the internal and external environment, (2) it transmits the message along neurons, (3) it integrates the information to formulate an appropriate response, and (4) it sends out signals to effector tissues or organs.
- Neurons are cells that are specialized for the reception and transmission of electrical signals. They have dendrites (which receive information and conduct signals toward the cell body) and axons (which conduct signals away from the cell body to another neuron or an effector).
- Afferent neurons conduct information from sensory receptors to interneurons, which integrate the information into a response. The response signals are passed to efferent neurons, which activate the effectors that perform the response.
- Glial cells provide structural and functional support to neurons. They help to maintain the balance of ions surrounding the neurons and form insulating layers around the axons.
- The central nervous system (CNS) consists of the brain and spinal cord. It communicates with the peripheral nervous system (PNS), which is made up of the afferent and efferent systems.
- A neural circuit consists of the receptor, the afferent neuron, the interneuron, the efferent neuron, and the effector. The simplest neural circuit is the reflex arc.

Questions

1. (a) Explain the functions of afferent neurons, efferent neurons, interneurons, and effectors.
   (b) Describe how they work together. K/U
2. What is the purpose of the nodes of Ranvier? K/U
3. Which nervous system cells provide a supporting role, rather than transmitting nerve impulses? What is their role? K/U
4. Why do you think reflexes have evolved to occur without the need for the brain to process the information? K/U
5. What is a reflex arc? Describe a simple example of a reflex arc. K/U
6. Neurofibromatosis type 1 is a genetic condition of the nervous system. It is characterized by skin spots with different colorations, and tumours in the nervous system. Use the Internet and other sources to research neurofibromatosis type 1. Prepare a brief report that summarizes the causes, symptoms, and treatments for this condition. Why do you think neurofibromatosis is significantly under-diagnosed? T/I C
7. Has a doctor ever tapped your knee with a rubber hammer? Checking your reflex actions is one of several ways in which a doctor can assess the functioning of your nervous system. Choose three reflexes, and use the Internet and other sources to conduct research on them. Determine the following information about each reflex:
   - a general description of the reflex
   - the person who discovered the reflex and how it was discovered
   - the neurological pathway that the nerve signals follow
   - the significance of the reflex in normal functioning
   - the reason why we test for the reflex

   Prepare a one-page report or create a 5 min audiovisual presentation to share the essential information about the three reflexes you researched. T/I C

WEB LINK

11.2 Nerve Signals

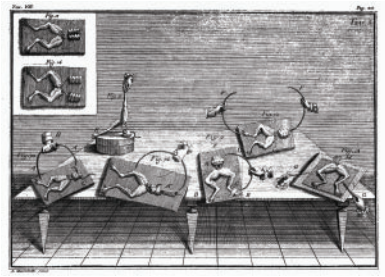


Figure 1 This is an artist's depiction of Galvani's laboratory, in which electrical conductivity was explored using the muscles of a dead frog.

Theories about the transmission of information through the nervous system date as far back as ancient Greece. The philosopher Alcmeon of Croton (540–500 BCE) discussed the presence of pores and channels in the brain and sensory organs. In 1781, Luigi Galvani, a doctor and physiologist at Italy's University of Bologna, discovered that the muscles of a dead frog would twitch when touched with different metals or an electric current (**Figure 1**). In his hypothesis of "animal electricity," he proposed that electric forces generated in the muscles travelled from the nerves to the muscles and were responsible for muscle contractions and movements. While we now know that his hypothesis was only partially correct, his work sparked an increased interest in neurology.

Instruments to detect electrical transmission within nerves and muscles were introduced in 1848, with the work of Emil DuBois-Reymond at the University of Berlin. By 1906, Dutch physiologist Willem Einthoven had refined a machine that could detect electric impulses in the heart muscle, a methodology that is now the basis of the electrocardiogram (ECG). In 1929, Hans Berger, a German psychiatrist, measured electric currents during brain activity by placing electrodes on a patient's skull. One of Canada's first neurologists was Sir William Osler (1849–1919). He published almost 200 works about neurological disorders, often drawing details from autopsies he had performed. CAREER LINK

Continued research on the nervous system began to reveal differences between electrical and neural transmission. For example, scientists discovered that nerve impulses travel much more slowly than electric current. The cytosol in the cell body of a neuron provides significant resistance to the transmission of currents. Another notable difference was that nerve impulses do not undergo loss of strength during transmission, unlike electric currents, whose strength declines with the distance they travel. Scientists discovered that nerves use internal cellular energy to generate current, whereas electric current can arise only from an external energy source.

Around 1900, German physiologist Julius Bernstein proposed the idea that nerve impulses are the result of ions moving through the nerve cell membrane. Two researchers from Columbia University, K.S. Cole and H.J. Curtis, provided evidence for Bernstein's theory using an electrode applied to the large neuron of a squid. When the nerve became excited, the electrical potential across the membrane rose rapidly from about –70 mV at rest to about +40 mV.

The development of our knowledge of the nervous system, from early ideas to our current understanding, illustrates the progressive nature of science. Scientific knowledge builds on previous understanding, and it changes as new evidence becomes available. Our understanding of the nervous system will continue to grow with future research.

synapse a functional connection between neurons or between neurons and effectors

chemical synapse a synapse in which a neurotransmitter moves from a presynaptic cell to a postsynaptic cell through the synaptic cleft

neurotransmitter a chemical that is released from vesicles into synapses to facilitate nerve signal transmission

synaptic cleft the tiny gap between presynaptic and postsynaptic cells in a chemical synapse, across which the neurotransmitter diffuses

Neural Communication via Synapses

A **synapse** is a site where a neuron makes a connection with either another neuron or an effector, such as a muscle fibre or gland. On one side of the synapse is the axon terminal of a presynaptic cell, which is the neuron that transmits the signal. On the other side is either a dendrite or the cell body of a postsynaptic cell, which is the neuron or effector (such as a muscle cell) that receives the signal. Depending on the kind of neuron, communication across a synapse may occur either chemically or electrically.

In the more common **chemical synapse**, a chemical messenger called a **neurotransmitter** is released by an axon terminal at the synapse. The plasma membranes of the presynaptic and postsynaptic cells are separated by a narrow gap, about 25 nm wide, called the **synaptic cleft** (**Figure 2(a)**, next page).

In an **electrical synapse**, the plasma membranes of the presynaptic and postsynaptic cells are in direct contact, allowing the current to flow directly from one neuron to the next (**Figure 2(b)**). When an electric impulse arrives at the axon terminal, a gap junction allows ions to flow directly between the two cells, providing unbroken transmission of the electrical signal. Electrical synapses allow for very rapid transmission and synchronous activity in a group of neurons.

electrical synapse a synapse in which the presynaptic cell makes direct contact with the postsynaptic cell, allowing current to flow via gap junctions between the cells

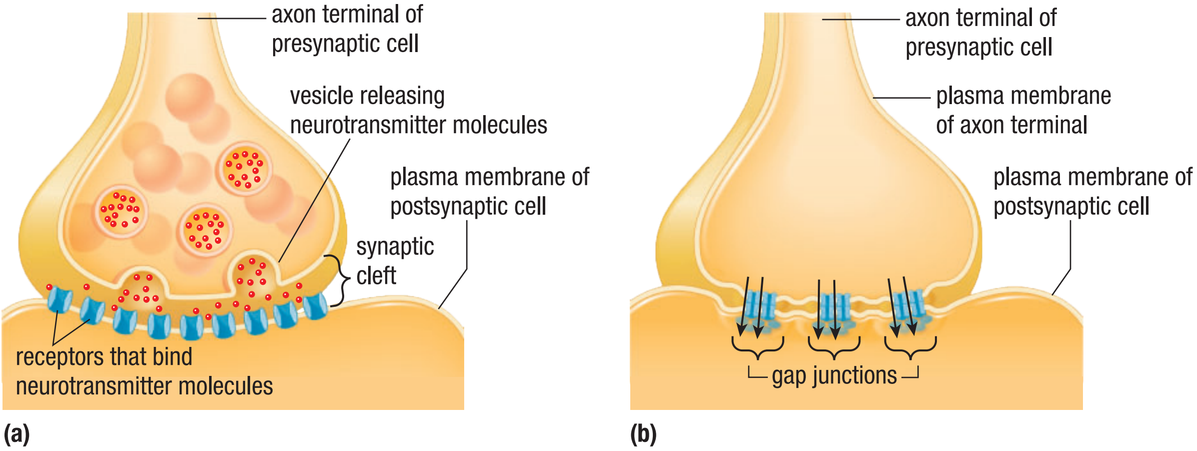

axon terminal of presynaptic cell
vesicle releasing neurotransmitter molecules
plasma membrane of postsynaptic cell
synaptic cleft
receptors that bind neurotransmitter molecules
(a)
axon terminal of presynaptic cell
plasma membrane of axon terminal
plasma membrane of postsynaptic cell
gap junctions
(b)

Figure 2 (a) In a chemical synapse, the neurotransmitter diffuses across the synaptic cleft and binds to a receptor in the plasma membrane of the postsynaptic cell. (b) Electrical signals transfer directly across gap junctions in an electrical synapse.

Conduction of Electrical Signals by Neurons

All animal cells have a separation of positive and negative charges across the plasma membrane. Outside the cell is positive, and inside the cell is negative. This charge separation, in part, produces a voltage, or electrical potential difference, across the plasma membrane. This potential difference is called the **membrane potential**. The membrane potential is caused by the uneven distribution of Na^+ and K^+ inside and outside the cell. Plasma membranes are selectively permeable—they allow some ions, but not others, to move across the membrane through embedded proteins called **ion channels**. Some ion channels are closed in their resting state, and they open only in response to a change in voltage. Other ion channels open upon the binding of a specific substance.

membrane potential the electrical potential of a membrane, which is caused by an imbalance of charges on either side of the membrane

ion channel a protein embedded in the plasma membrane that allows ions to pass through it

In most cells, the membrane potential remains stable. Neurons and muscle cells, however, respond to electrical, chemical, mechanical, and certain other stimuli, causing their membrane potential to change rapidly. Cells with this property are said to be excitable. Excitability, produced by a sudden flow of ions across the plasma membrane, is the basis for nerve impulse generation.

Resting Membrane Potential

A special ion channel, the Na^+/K^+ active transport pump, uses energy from ATP hydrolysis to pump three Na^+ out of the cell for every two K^+ pumped in, generating a higher Na^+ concentration outside the cell and a higher K^+ concentration inside the cell (**Figure 3**, next page). This explains the net positive charge outside the cell. The inside of the cell has additional negative charge because the cell also contains many anions (negatively charged ions).

The membrane of a typical neuron that is not conducting an impulse exhibits a steady negative membrane potential of about –70 mV. This is called the **resting potential**. A cell with a resting potential other than 0 V (that is, a cell with some separation of charge on either side of its membrane) is said to be polarized. The Na^+/K^+ pump creates the imbalance of Na^+ and K^+ inside and outside the cell. The concentration of anions within the cell results in the inside being negatively charged and the outside being positively charged.

resting potential the voltage difference across a nerve cell membrane of an unstimulated neuron; usually negative

Charged particle concentrations (mM)		
	Inside	Outside
Na^+	15	150
K^+	150	5
A^-	100	0

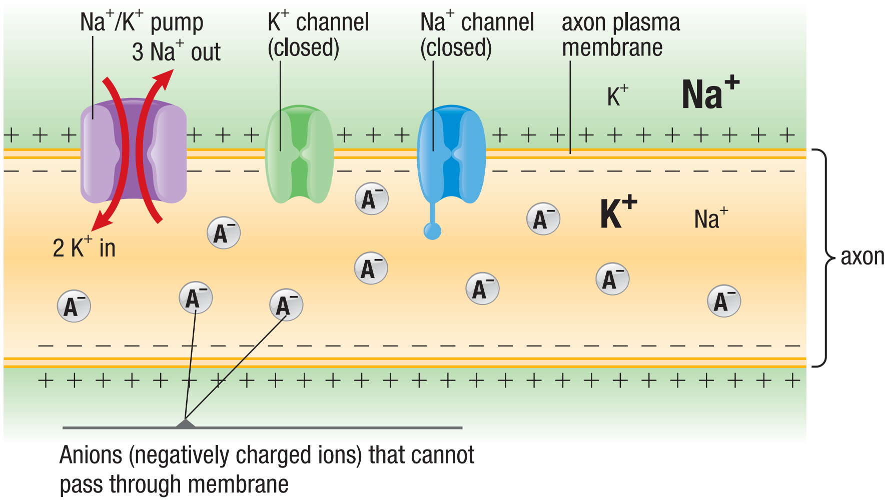


Figure 3 The distribution of ions inside and outside an axon produces the resting potential, –70 mV. Note that the Na^+ and K^+ ion channels are closed when the membrane is at the resting potential.

Action Potential

When a neuron conducts an electric impulse, there is an abrupt and temporary change in membrane potential. This is called an **action potential**. An action potential begins as a stimulus that causes positive charges from outside the neuron to flow inward, making the interior side of the membrane less negative.

action potential the voltage difference across a nerve cell membrane when the nerve is excited

In phase 1 of an action potential (**Figure 4**), the incoming positive ions raise the membrane potential (which was polarized at rest) to a less negative value. This is called depolarization. If depolarization continues, when the membrane potential reaches a level called the **threshold potential** (about –50 to –55 mV in a typical neuron), Na^+ channels open. In phase 2 (above threshold), Na^+ channels continue to open and Na^+ flows inward along its concentration gradient. The action potential then fires, causing the membrane potential to increase sharply. In less than 1 ms, the action potential rises so high that the inside of the plasma membrane becomes positive because of the influx of positive ions

threshold potential the potential at which an action potential is generated by a neuron

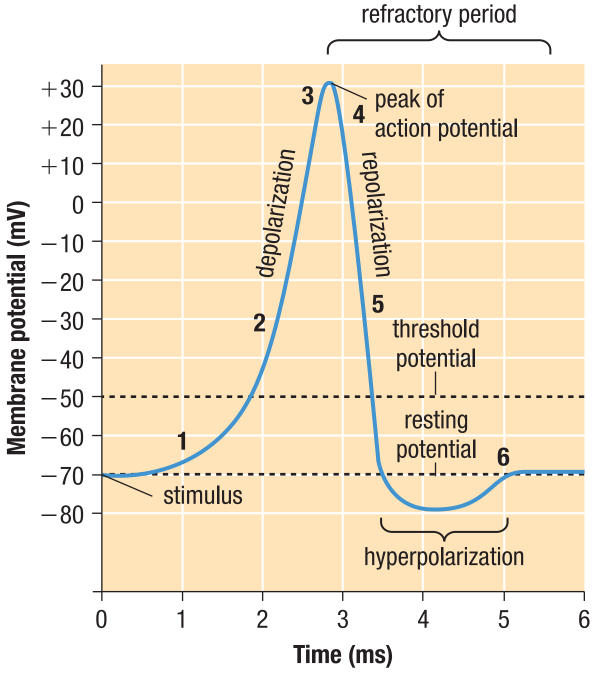


Figure 4 Changes in membrane potential during the six phases of the action potential

across the membrane. In phase 3, the action potential reaches its peak, momentarily reaching a value of +30 mV or more. The interior of the neuron is relatively positive. The Na$^+$ channels close and become inactive, and the K$^+$ channels open and allow K$^+$ to exit (phase 4). The outward flow of K$^+$ along its concentration gradient causes the membrane potential to fall rapidly during the process of repolarization. In phase 5, the voltage-gated K$^+$ channels begin to close slowly. The slow closure allows the membrane to undershoot its resting value briefly as it repolarizes. In phase 6, the final phase, the membrane potential stabilizes at the resting value and is ready for a new action potential.

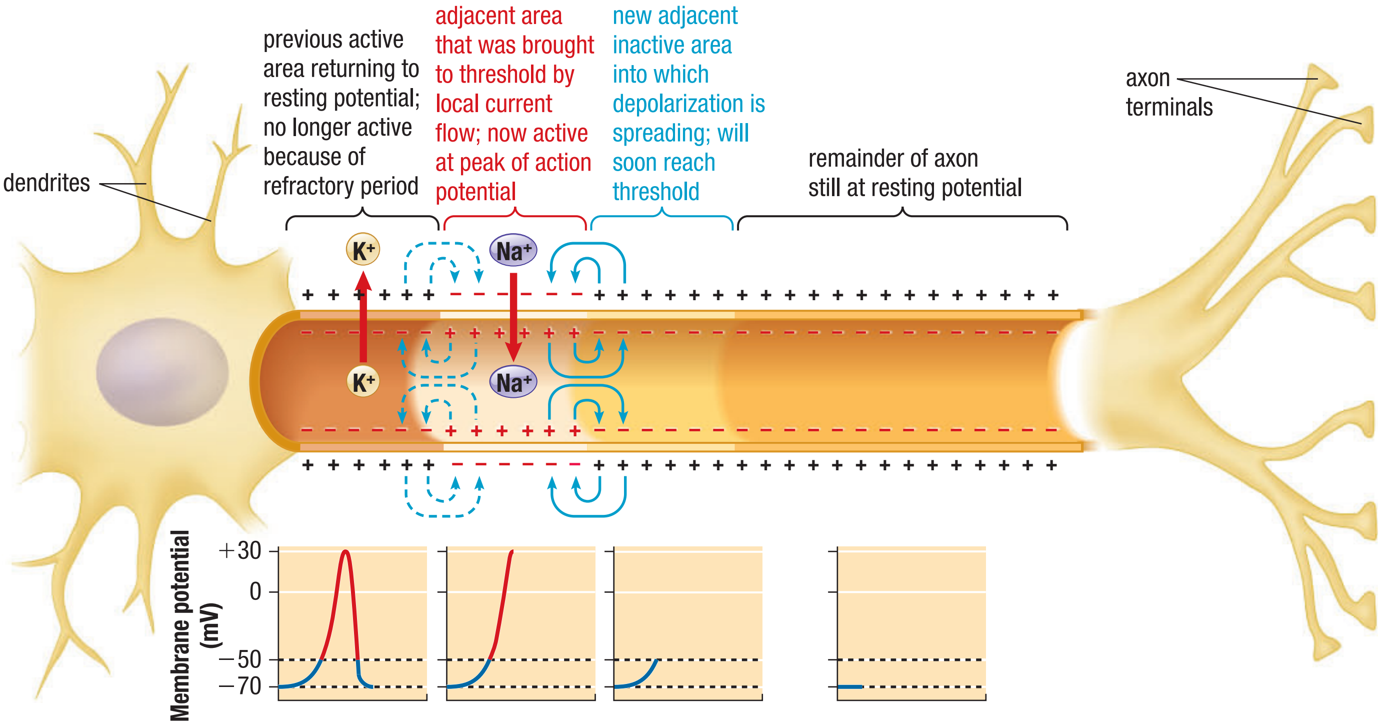
When the potential is below the resting value, the membrane is said to be hyperpolarized. The entire change, from the initiation of the action potential to the return to the resting potential, takes less than 5 ms in the fastest neurons. An action potential takes the same basic form in all neurons. However, different types of neurons exhibit differences in the value of the resting potential and the peak of the action potential, and in the time required to return to the resting potential.

Many stimuli cause some degree of depolarization of a neuron, but an action potential is produced only if the stimulus is strong enough to cause the depolarization to reach the threshold. This is referred to as the all-or-nothing principle. Once triggered, the changes in membrane potential take place independently of the strength of the stimulus.

Once an action potential is initiated at the dendrite end of a neuron, it passes along the surface of a nerve or muscle cell as an automatic wave of depolarization. It travels away from the stimulation point, without requiring further triggering events. This is called propagation of the action potential.

Beginning at the peak of an action potential, the membrane enters a resting period, or **refractory period**, of a few milliseconds. During the refractory period, the threshold that is required for generation of an action potential is much higher than normal. The refractory period lasts until the membrane has stabilized at the resting potential. It keeps impulses travelling in a one-way direction in the neurons. This is because, once ion channels are opened to their activated state, they need time to reset to their original position before they can open again. Therefore, only downstream ion channels are able to open, ensuring the one-way movement of the action potential along the axon toward the axon terminals (**Figure 5**).

refractory period the period of time during which the threshold required for the generation of an action potential is much higher than normal



previous active area returning to resting potential; no longer active because of refractory period
adjacent area that was brought to threshold by local current flow; now active at peak of action potential
new adjacent inactive area into which depolarization is spreading; will soon reach threshold
axon terminals
dendrites
remainder of axon still at resting potential
K+
Na+
K+
Na+
Membrane potential (mV)
+30
0
−50
−70

Figure 5 The action potential proceeds along the axon with a domino effect. Each rapid change in potential triggers a change in potential in the adjacent region, causing the action potential to move along the axon in a wave of depolarization.

The magnitude of an action potential stays the same as it travels along an axon, even where the axon branches at its tips. Thus, the propagation of an action potential resembles a fuse that burns with the same intensity along its length and along any branches once it is lit. Unlike a fuse, however, an axon is not spent. It can fire another action potential of the same intensity within a few milliseconds after the first has passed through.

The all-or-nothing characteristic of the action potential means that the intensity of a stimulus is reflected in the frequency of action potentials rather than in their magnitudes. (Within the same neuron, they are all the same magnitude.) The greater the stimulus, the faster the action potentials, up to a rate determined by the physical limitations of the neuron—usually between 10 and 100 per second! The rate of conduction increases with the diameter of the axon. While large axons can conduct impulses as rapidly as 25 m/s, they take up a large amount of space.

Conduction in Myelinated Axons

In jawed vertebrates, a specialized mechanism allows action potentials to hop rapidly along axons instead of burning smoothly like a fuse. Conduction by hopping relies on the gaps in the insulating myelin sheath that surrounds many axons. These gaps, known as nodes of Ranvier, expose the axon membrane to extracellular fluids. Na^+ and K^+ channels, which are crowded into the nodes, allow action potentials to develop at these positions, jumping rapidly from one node to the next. The inward movement of Na^+ ions produces depolarization, but the excess positive ions are unable to leave the axon through the membrane regions covered by the myelin sheath. Instead, they diffuse rapidly to the next node, where they cause depolarization, inducing an action potential at that node. As the mechanism repeats, the action potential jumps rapidly along the axon from node to node. This hopping form of conduction proceeds at rates of up to 130 m/s, which is much faster than the transmission rate of about 1 m/s in an unmyelinated axon of the same diameter.

Conduction by hopping allows thousands to millions of fast-transmitting axons to be packed into a relatively small diameter. For example, the optic nerve in humans, which leads from the eye to the brain, is only 3 mm in diameter but is packed with more than a million axons. If these axons were unmyelinated, each would have to be about 100 times as thick to conduct impulses at the same velocity. This would produce an optic nerve of about 300 mm in diameter!

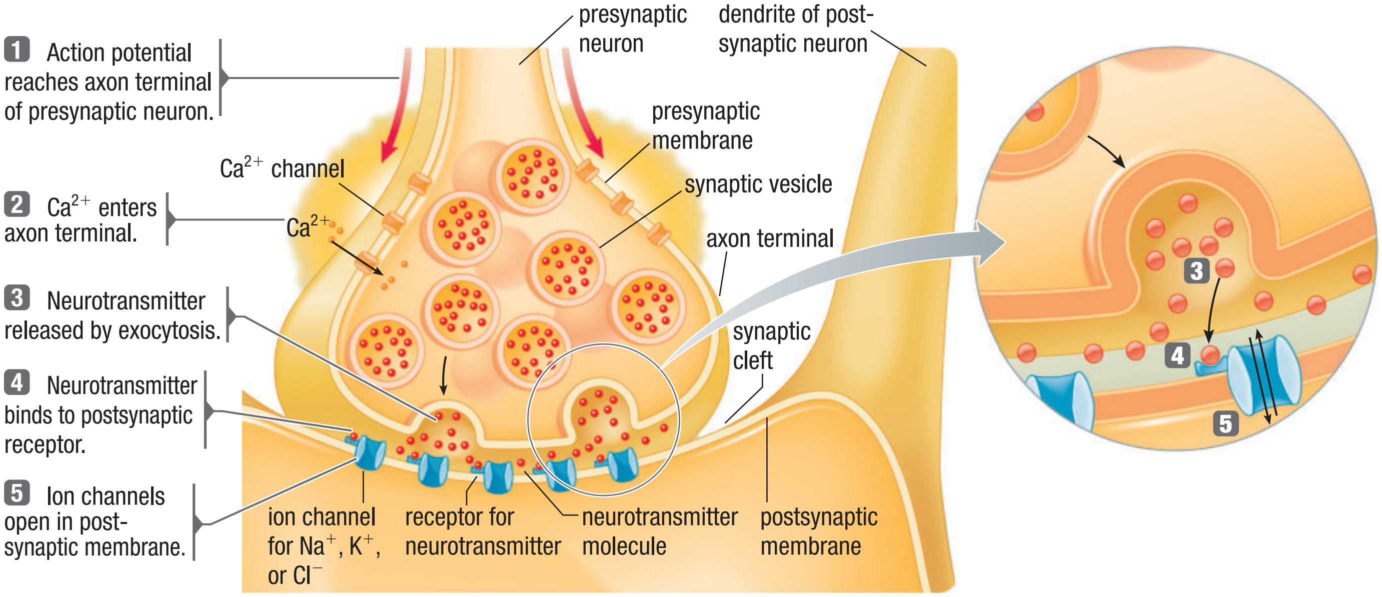
The disease multiple sclerosis (from *sclero* meaning "hard") underscores the importance of myelin sheaths in the operation of the vertebrate nervous system. In multiple sclerosis, myelin is attacked by the immune system and is progressively lost from axons and replaced by hardened scar tissue. The changes block or slow the transmission of action potentials, producing numbness, muscular weakness, faulty coordination of movements, and paralysis that worsens as the disease progresses. Although clear genetic factors are involved, research shows that environment may also play a role. For example, the incidence of the disease increases with the distance from the equator. The incidence in Canada, 2.4 people per 1000 population, is one of the highest in the world.

Conduction across Chemical Synapses

The vast majority of vertebrate neurons communicate by means of neurotransmitters. Action potentials are transmitted directly across electrical synapses, but they cannot jump across the synaptic cleft in a chemical synapse. The time required for the release, diffusion, and binding of neurotransmitters across a chemical synapse delays transmission, whereas the transmission of impulses across an electrical synapse is almost instantaneous. However, communication through chemical synapses allows neurons to receive input from hundreds to thousands of axon terminals at the same time.

Neurotransmitters are stored in synaptic vesicles in the cytosol of an axon terminal. Ca^{2+} ions are constantly pumped out of the cell by an active transport protein in the plasma membrane, keeping their concentration higher outside than inside.

As an action potential arrives, the Ca^{2+} channel gates in the axon terminal open, allowing Ca^{2+} to flow back into the cytosol. The rise in the Ca^{2+} concentration triggers a protein in the membrane of the synaptic vesicle. This protein allows the vesicle to fuse with the plasma membrane, releasing neurotransmitter molecules into the synaptic cleft by exocytosis (**Figure 6**).



1 Action potential reaches axon terminal of presynaptic neuron.
2 Ca^{2+} enters axon terminal.
3 Neurotransmitter released by exocytosis.
4 Neurotransmitter binds to postsynaptic receptor.
5 Ion channels open in post-synaptic membrane.
presynaptic neuron
dendrite of post-synaptic neuron
presynaptic membrane
Ca^{2+} channel
synaptic vesicle
Ca^{2+}
axon terminal
synaptic cleft
ion channel for Na^+, K^+, or Cl^-
receptor for neurotransmitter
neurotransmitter molecule
postsynaptic membrane
3
4
5

Figure 6 A chemical synapse, facilitated by a neurotransmitter

The neurotransmitter molecules diffuse across the cleft and bind to receptor molecules in the membrane of the postsynaptic cell. The binding of the neurotransmitter opens gated ion channels, allowing ions to flow into the dendrite or cell body of the postsynaptic neuron. Some neurotransmitters have stimulatory effects, whereas others have inhibitory effects. Most neurotransmitters work by opening or closing membrane-embedded ion channels that conduct Na^+ or K^+ across the postsynaptic membrane. Some regulate Cl^- (chloride ions).

If the postsynaptic neuron becomes depolarized to the point of threshold, it will generate a new action potential that travels along its axon to reach a synapse with the next neuron or effector in the circuit. A chemical synapse is more than a simple on/off switch. Many factors can influence the generation of a new electrical impulse in the postsynaptic cell, including neurotransmitters that inhibit that cell rather than stimulate it. The balance of stimulatory and inhibitory effects in chemical synapses contributes to the integration of incoming information in a receiving neuron.

Neurotransmitters

Nearly 100 different substances are known or suspected to be neurotransmitters. Most of them are relatively small molecules that diffuse rapidly across the synaptic cleft. Some axon terminals release only one type of neurotransmitter, whereas others release several types.

One of the best-known neurotransmitters is acetylcholine. In humans, it triggers muscle contraction, stimulates hormone secretion, and is involved in wakefulness, attentiveness, memory, learning, anger, aggression, and sexuality. Acetylcholine-releasing neurons in the brain degenerate in people who develop Alzheimer's disease, causing memory, speech, and perceptual abilities to decline. Acetylcholine is the target of many natural and artificial poisons. Curare, a plant extract that is used as an arrow poison by some Indigenous peoples of South America, blocks muscle contractions and produces paralysis by competing directly with acetylcholine for binding sites in the synapses that control muscle cells. Nicotine (the drug released from smoking tobacco) also binds to acetylcholine receptors, but it acts as a stimulant by turning the receptors on rather than off.

Other substances can block the operation of these neurotransmitters. For example, tetanus toxin, released by the bacterium *Clostridium tetani*, blocks the neurotransmitter in the synapses that control muscle contractions. The body muscles contract so forcibly that the body arches painfully and the teeth become tightly clenched, giving the condition its common name—lockjaw. Once the effects extend to the respiratory muscles, the victim quickly dies. The disease is entirely preventable, thanks to vaccination with inactivated tetanus toxin.

Neurotransmitters called endorphins are released during pleasurable experiences (such as eating or sexual intercourse) or physical stress (such as childbirth or extended physical exercise). These neurotransmitters have the opiate-like property of reducing pain and inducing euphoria, well known to exercise enthusiasts as a pleasant by-product of their physical efforts (Section 11.4.).

Octopamine is a neurotransmitter involved in insect-feeding activities. It has recently been linked to bee waggle-dance behaviour and is also associated with firefly flashing.

Investigation **11.2.1**

Investigating the Nervous System of an Invertebrate (p. 555)

You have learned how nerve cells communicate. In this investigation, you will investigate how an organism senses and responds to its environment.

Research This

Neurological Disorders

Skills: Researching, Predicting, Planning, Analyzing, Evaluating, Communicating, Defending a Decision

SKILLS HANDBOOK **A4.1**

When neural signalling is hampered by drugs, injury, or disease, there can be profound implications for the functioning of the human body. In this activity, you will choose one of the following neurological diseases or disorders to research in detail: Parkinson's disease, Alzheimer's disease, Huntington disease, ALS (amyotrophic lateral sclerosis), NF2, Schwannomatosis, brain injury, or concussion.

1. Working with a partner, use the Internet and other sources to research one of the diseases or disorders listed above. Use the following points to guide your research:
   - the causes, symptoms, and treatments
   - the methods of diagnosis
   - recent research and advancements (preferably Canadian) in prevention and/or treatment
   - the impact of the disease/disorder on the individual, the family, the medical system, and society
2. As you do your research, keep detailed notes and record the reference information for each source.

A. With your partner, prepare a fictitious interview with an expert on the disease/disorder. The expert should be a person you have learned about through your research. Write five to seven questions you could ask this expert about the disease/disorder, and prepare detailed answers based on your research. T/I C

B. Prepare and present the interview in the form of a magazine article, a recorded audio interview, a video interview, or another format approved by your teacher. T/I C

C. Describe how you think the disease/disorder affects the everyday life of an individual who suffers from it. T/I A

D. Do you think the disease/disorder has implications for the medical system and society? Explain. A

E. Do you think it is better to focus future research on the prevention, treatment, or cure of the disease/disorder? Use information from your research to justify your opinion. T/I C

WEB LINK

11.2 Review

Summary

- Neurons make connections using two types of synapses: electrical and chemical.
- In an electrical synapse, impulses pass directly from the sending cell to the receiving cell by ion flow through gap junctions.
- The unequal distribution of positive and negative charges on either side of a neuron's cell membrane establishes a potential difference called the resting potential. It results from an active transport pump that sets up concentration gradients of Na^+ ions (higher outside) and K^+ ions (higher inside).
- An action potential is generated when a stimulus pushes the resting potential to the threshold value at which Na^+ channels open in the plasma membrane. The inward flow of Na^+ changes the membrane potential abruptly from a negative peak to a positive peak, opening the K^+ channels.
- Action potentials move along an axon as the ion flows generated in one location on the axon depolarize the potential in an adjacent location. Action potentials are prevented from reversing direction by a brief refractory period.
- In chemical synapses, neurotransmitters released from the presynaptic cell bind to the postsynaptic cell. This alters the flow of ions across the cell membrane and pushes the membrane potential toward or away from the threshold.

Questions

1. Why does neural signalling proceed in only one direction? K/U
2. Explain the movement of ions in a neuron that has each membrane potential. A
   (a) −70 mV
   (b) −51 mV
   (c) −49 mV
   (d) 0 mV
   (e) +30 mV
3. In multiple sclerosis, myelin is progressively lost from axons and replaced by hardened scar tissue. Given what you have learned about the function of myelin, explain how the degradation of myelin might affect the transmission of nerve impulses. T/I
4. Use the Internet and other sources to learn about active Canadian research on multiple sclerosis or another nervous system disorder that interests you. Explain your findings in a one-page summary. T/I C
5. (a) If an axon were severed, would the reception of a nerve impulse or the transmission of a nerve impulse be affected? Explain.
   (b) How could you use this information to design a technology that could help a patient who has had nerves severed?
   (c) What features would you have to include in your design to accommodate both the afferent and efferent signals? A

WEB LINK

11.3 The Central Nervous System

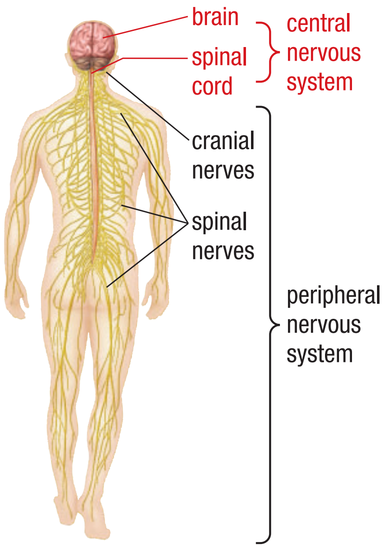


Figure 1 The central and peripheral nervous systems and their subsystems

When you hear the term "nervous system," do you think of the brain and the spinal cord? While the central nervous system is the core of the nervous system, the nervous system is actually much more extensive. In vertebrates, the nervous system is made up of the central nervous system (CNS) and the peripheral nervous system (PNS). The CNS consists of the brain and spinal cord, and the PNS consists of the nerves that connect the brain and spinal cord to the rest of the body (**Figure 1**).

The complexity of the human brain is what distinguishes humans from other animals and allows us to have complex behaviours, including language and the ability to develop culture and civilization. Humans have the most complex nervous system of all animals. Nevertheless, we have the same basic brain regions that are found in simpler vertebrates. The most significant changes in the evolution of the human brain have occurred in the region associated with reason, intellect, memory, language, and personality. Our reasoning ability, rather than the acuity of our senses, is what makes the human brain unique.

Nervous systems develop in different ways in different taxa. Vertebrates are thought to have evolved from the larval form of a primitive chordate. In chordates, the nervous system is formed dorsally as a hollow neural tube. The anterior end of the neural tube develops into the brain and the rest develops into the spinal cord. During development in vertebrates, the central cavity of the neural tube becomes the fluid-filled ventricles of the brain and the narrow central canal of the spinal cord.

The organization of the brain is exceedingly complex. One way to understand its complexity is to examine its development from the embryonic neural tube. A generalized vertebrate brain, approximately midway through its embryonic development, shows the principal regions found in all vertebrate brains. Early in embryonic development, the anterior part of the neural tube enlarges into three distinct regions. The forebrain was originally associated with olfaction or the sense of smell, the midbrain was primarily associated with vision, and the hindbrain was mainly associated with balance (**Figure 2**).

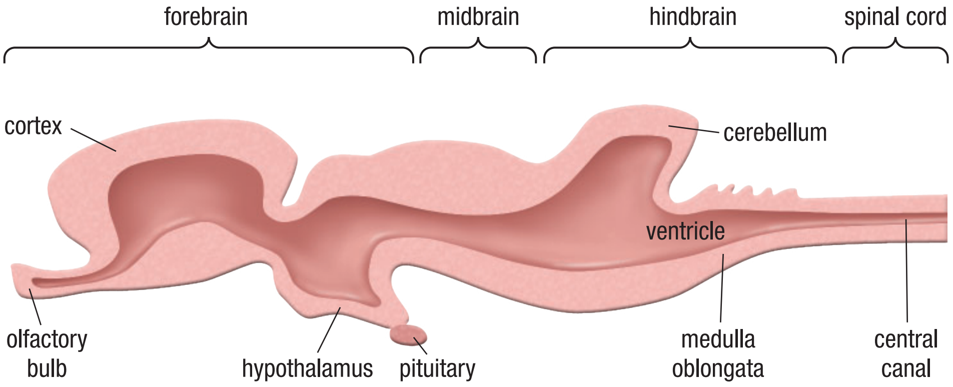


Figure 2 During the midway development of vertebrates, the brain is elongated. In later development in birds and mammals, the brain becomes folded so that the very prominent forebrain lies above the other regions and the size of the ventricle is reduced.

meninges three layers of connective tissue that surround and protect the brain and spinal cord

cerebrospinal fluid circulating fluid that surrounds the membranes of the brain and spinal cord; provides neural connection to the endocrine system

The brain and spinal cord are surrounded with, and protected by, three layers of connective tissue called the **meninges** (from *meninga* meaning "membrane"), and the **cerebrospinal fluid**. The cerebrospinal fluid circulates through the central canal of the spinal cord, through the ventricles of the brain, and between two of the meninges. It cushions the brain and spinal cord from jarring movements and impacts, nourishes them, and protects them from toxic substances.

The CNS manages body activities by integrating incoming sensory information from the PNS into compensating responses. It functions as the control centre of the body. In this section, you will examine the vertebrate CNS, beginning with the spinal cord and then moving on to the brain and its functions.

Spinal Cord

The spinal cord extends from the base of the brain down through a canal inside the vertebrae of the backbone. It carries impulses between the brain and the PNS and contains the interneuron circuits that control motor reflexes. In cross-section, the spinal cord has a butterfly-shaped core of **grey matter**, which consists of nerve cell bodies and dendrites. The grey matter is surrounded by **white matter**, which consists of axons, many of them surrounded by myelin sheaths (**Figure 3**). Pairs of spinal nerves connect with the spinal cord at spaces between the vertebrae.

grey matter the tissue of the brain and spinal cord where the cell bodies and dendrites of neurons are located

white matter the tissue of the brain and spinal cord, composed primarily of axons of neurons; in the spinal cord, it surrounds the grey matter

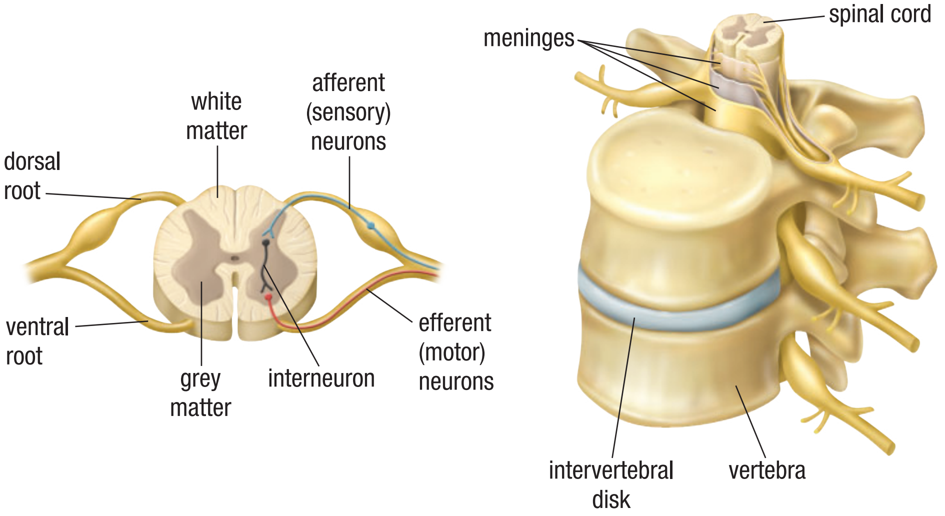


Figure 3 The spinal cord is protected by the vertebral column. Afferent (sensory) nerves enter the spinal cord through the dorsal root, and efferent nerves leave through the ventral root.

Afferent (incoming) axons enter the dorsal root of the spinal cord and make synapses with interneurons in the grey matter. The interneurons send axons upward through the white matter of the spinal cord to the brain. Efferent (outgoing) axons from the interneurons of the brain pass downward through the white matter of the cord and make synapses with the dendrites and cell bodies of efferent neurons in the grey matter of the cord. Axons from these efferent neurons exit the spinal cord through the ventral root of the spinal nerves. Efferent nerves in the ventral root carry information from the spinal cord to the peripheral muscles, organs, and glands.

Brain

The brain is the major centre that receives, integrates, stores, and retrieves information. Its interneuron networks generate responses that provide the basis for our voluntary movements, consciousness, behaviour, emotions, learning, reasoning, language, and memory, as well as many other complex activities. The three major divisions of the embryonic brain give rise to the structures of the adult brain. Like the spinal cord, each brain structure contains both grey matter and white matter and is surrounded by meninges and circulating cerebrospinal fluid.

The hindbrain of vertebrates develops into the **medulla oblongata** (commonly known as the medulla) and the **cerebellum**. The medulla contains the nerve centres that deal with involuntary behaviours, such as breathing, digestion, heart rate, and blood pressure. The cerebellum plays a major role in motor responses (voluntary movements of the skeletal muscles) and is responsible for balance and fine motor control. In higher mammals, a mass of fibres that connects the cerebellum to higher centres in the brain is so prominent that it is identified as the **pons** (bridge). The medulla and the pons, along with the midbrain, form a stalklike structure known as the

medulla oblongata the hindbrain region that connects the spinal cord to the cerebellum; important in autonomic nerve control

cerebellum the hindbrain region that is involved in muscle movement and balance

pons the brain region that transfers nerve signals between the cerebellum and the medulla brain stem, which connects the forebrain to the spinal cord. Ten pairs of nerves originate from the brain stem to serve the head, neck, and body trunk areas. The forebrain, which makes up most of the brain mass in humans, forms the **cerebrum**. The cerebrum is the most developed part of the brain. It controls most of the sensory and motor activities (**Figure 4**).

cerebrum the brain region that is involved in motor activities and sensory information; the largest and most developed region of the brain

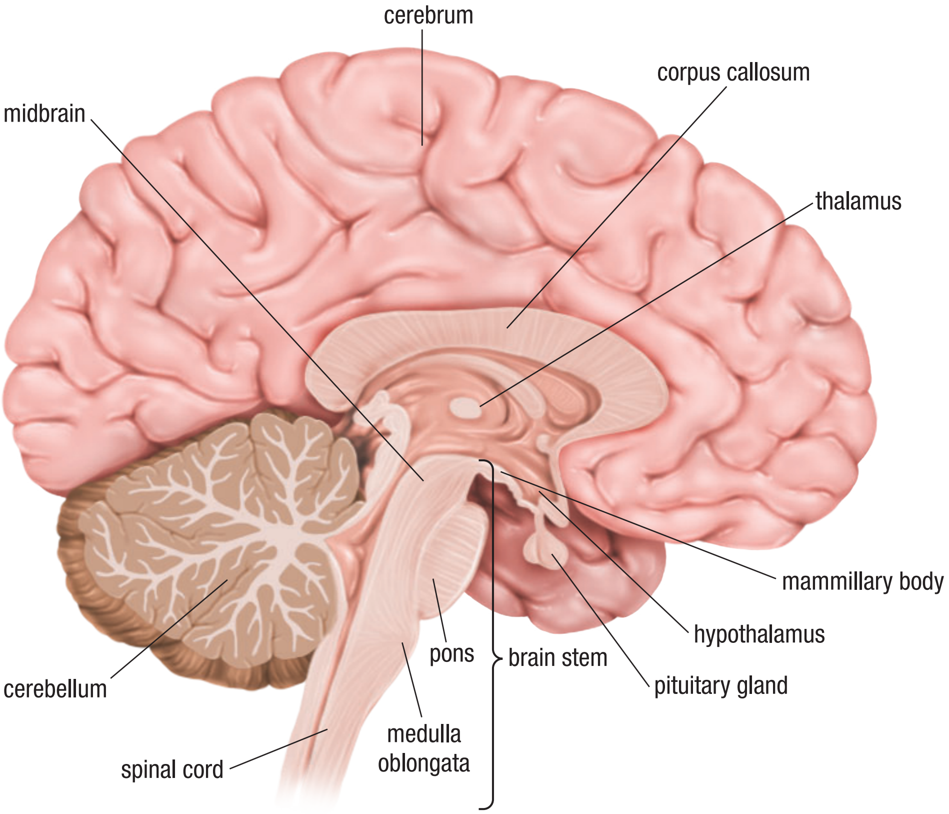


Figure 4 The adult brain loses the elongated structure of the embryonic brain. The cerebrum, which develops from the forebrain, folds to cover the regions of the brain that develop from the midbrain and hindbrain.

One of the trends in the evolution of the brain was the increasing prominence of the cerebrum. Beginning with reptiles, the cerebrum increased in size relative to the rest of the brain. In mammals, folds appeared, increasing the amount of brain surface area within a particular volume. The total mass of the brain relative to the size of the animal increased as well, permitting animals to undertake more complex tasks.

Cerebral Cortex

cerebral cortex the outermost layer of the cerebral hemispheres

The surface layer of the cerebrum, the **cerebral cortex**, is a thin layer of grey matter in which numerous unmyelinated neurons are found. It carries out all of the higher brain functions. The cerebrum is divided into right and left cerebral hemispheres. It is corrugated by fissures and folds that increase the surface area of the cerebral cortex and divide the brain into the frontal, parietal, temporal, and occipital lobes (**Figure 5**, next page). This structure reflects two of the evolutionary tendencies in the brains of mammals: the corrugation of the hemispheres and the development of a layer of grey matter on the periphery.

The two cerebral hemispheres can function separately. Each has its own communication lines internally and with the rest of the CNS and the body. The left hemisphere responds primarily to sensory signals from, and controls movements in, the right side of the body. The right hemisphere has the same relationship with the left side of the body. The opposite connection and control reflect the fact that the nerves carrying afferent and efferent signals cross from left to right within the spinal cord or brain stem. Thick axon bundles, which form a structure called the corpus callosum, connect the two cerebral hemispheres and coordinate their functions.

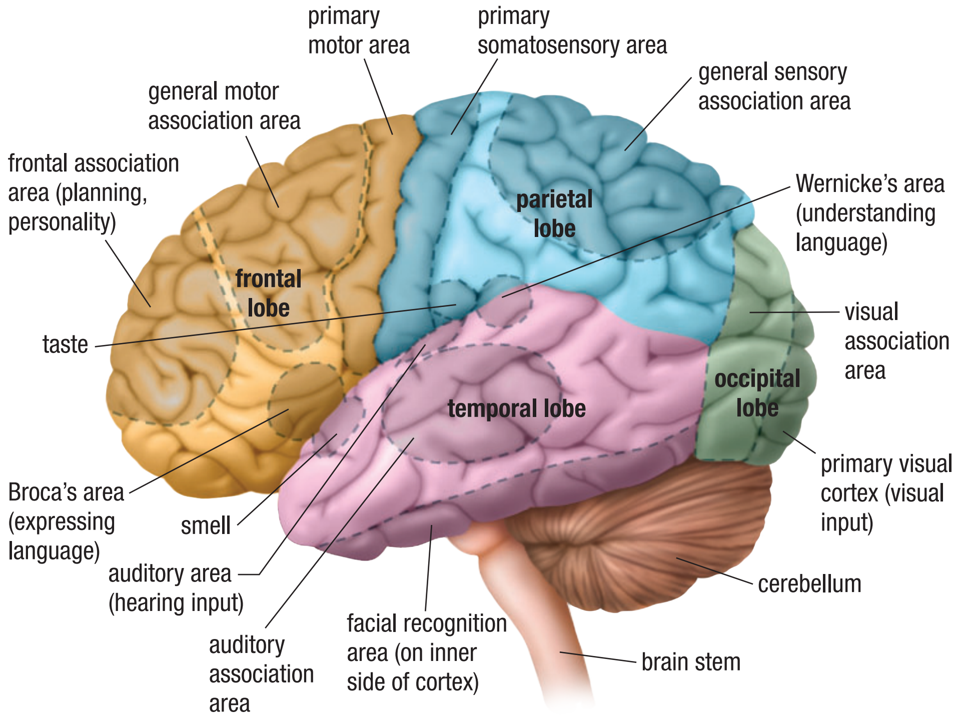

primary motor area
primary somatosensory area
general sensory association area
general motor association area
frontal association area (planning, personality)
parietal lobe
Wernicke's area (understanding language)
frontal lobe
taste
visual association area
occipital lobe
temporal lobe
primary visual cortex (visual input)
Broca's area (expressing language)
smell
auditory area (hearing input)
cerebellum
facial recognition area (on inner side of cortex)
brain stem
auditory association area

Figure 5 The cerebral cortex of the lobes of the cerebrum is divided into major regions and association areas.

SENSORY REGIONS OF THE CEREBRAL CORTEX

Areas that receive and integrate sensory information are distributed over the cerebral cortex. In each hemisphere, the primary somatosensory area, which registers information about touch, pain, temperature, and pressure, runs in a band across the parietal lobes of the brain. Other sensory regions of the cerebral cortex have been identified with hearing, vision, smell, and taste. The primary motor area of the cerebral cortex runs in a band across the frontal lobe, just in front of the primary somatosensory area.

In the primary somatosensory and motor areas, some body parts (such as the lips and fingers) are represented by large regions, and other body parts (such as the arms and legs) are represented by relatively small regions. The relative sizes produce a distorted image of the human body (**Figure 6**, next page) that is quite different from the actual body proportions. The differences are reflected in the precision of touch and movement in structures such as the lips, tongue, and fingers.

Cerebellum

The cerebellum has a folded structure that increases its relative size. It is connected to the pons, but it is separate in structure and function from the brain stem. Through its extensive connections with other parts of the brain, the cerebellum receives sensory input that originates from receptors in the muscles and joints; from balance receptors in the inner ear; and from the receptors of touch, vision, and hearing. The sensory input conveys information about how the body trunk and limbs are positioned, in which direction they are moving, and the degree to which different muscles are contracted or relaxed. The cerebellum integrates this input and compares it with signals from the cerebrum that control voluntary body movements. Output from the cerebellum to the cerebrum, brain stem, and spinal cord modify and fine-tune body movements to keep the body in balance and directed toward targeted positions in space.

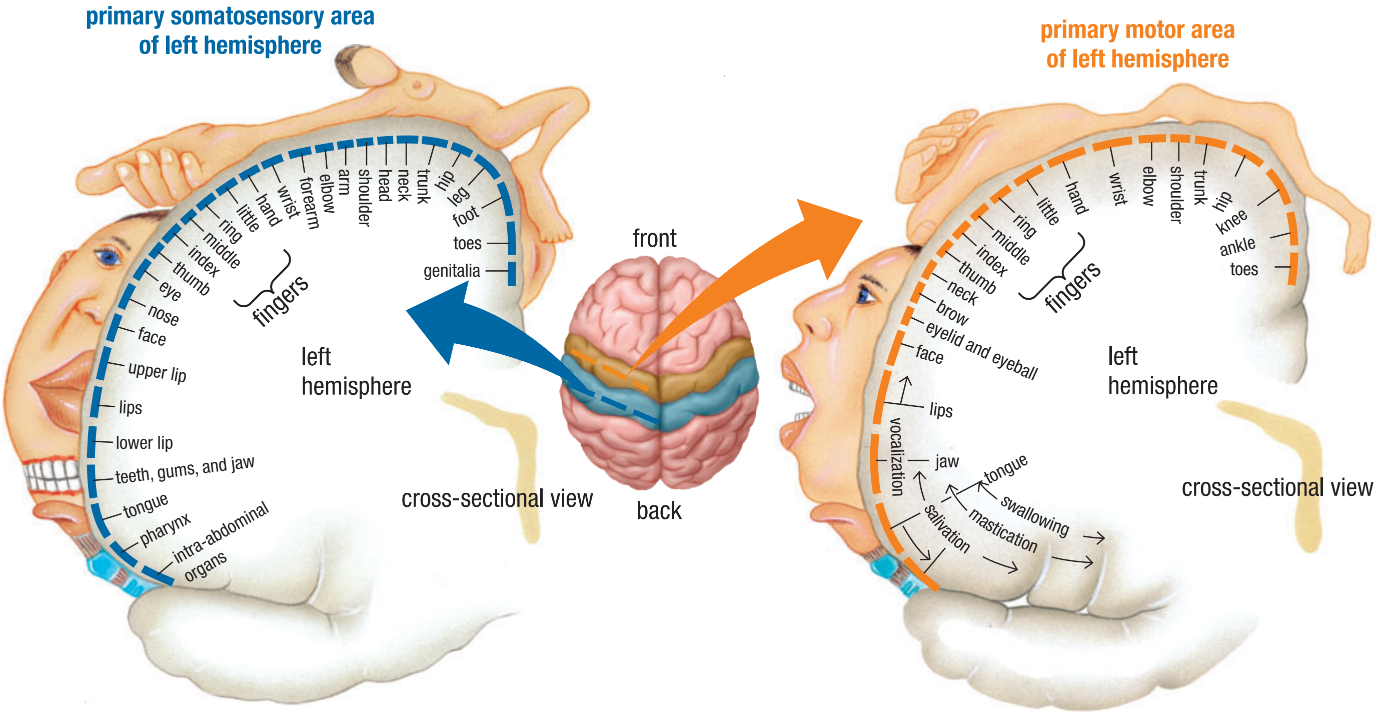


Figure 6 The primary somatosensory and motor areas of the cerebrum form a band across the top of the brain. The distorted images of the human body show the relative areas of the sensory and motor cortex devoted to different body regions.

Thalamus, Hypothalamus, and Basal Nuclei

thalamus the brain region that interprets sensory input and signals the cerebrum

The **thalamus** forms a major switchboard that receives sensory information and relays it to the appropriate regions of the cerebral cortex. As well, it plays a role in alerting the cerebral cortex to full wakefulness or in inducing drowsiness or sleep.

The hypothalamus is a relatively small conical area that occurs in all vertebrates. It contains centres that regulate basic homeostatic functions of the body. Some of these centres set and maintain body temperature by triggering reactions such as shivering or sweating. Others constantly monitor the osmotic balance of the blood by testing its composition of ions and other substances. The hypothalamus is an important part of the endocrine system. It produces some of the hormones that are released by the pituitary gland and governs the release of other pituitary hormones.

The basal nuclei are grey-matter centres that surround the thalamus on both sides of the brain. They moderate the voluntary movements that are directed by motor centres in the cerebrum. Damage to the basal nuclei can affect the planning and fine-tuning of movements. This can lead to stiff, rigid motions of the limbs and unwanted or misdirected motor activities, such as tremors of the hands. Parkinson's disease, in which affected individuals exhibit all of these symptoms, results from degeneration of centres in and near the basal nuclei.

Blood–Brain Barrier

blood–brain barrier a barrier formed by tight junctions between endothelial cells in the capillaries in the brain that blocks the movement of most substances into the brain via the bloodstream

The brain is somewhat isolated from other parts of the body, so many substances that enter the body are unable to enter the brain. Unlike the epithelial cells that line the capillary walls elsewhere in the body and allow small molecules and ions to pass freely from the blood to the surrounding fluids, the endothelial cells that form capillaries in the brain have tight junctions between them. The tight junctions set up a **blood–brain barrier** that prevents most substances dissolved in the blood from entering the cerebrospinal fluid. This offers protection for the brain and spinal cord from infection by viruses, bacteria, and toxic substances that may circulate in the blood. Infections of the brain are rare, but not impossible. While the blood–brain barrier normally prevents cells, such as white blood cells, from entering the brain, an immune response activates

T-cells that are able to cross the barrier. The blood–brain barrier also allows a more stable composition of the cerebrospinal fluid, protecting it from the wide fluctuations that occur in blood in response to meals and other factors. This maintains a stable environment for neurotransmission.

Some areas of the brain, the circumventricular organs, are not behind the blood–brain barrier. For example, in the part of the hypothalamus involved in communication with the pituitary gland, the blood vessels do not have tight junctions, allowing direct exposure to the bloodstream. The pineal gland, which secretes melatonin directly into the bloodstream, is also not protected by the blood–brain barrier.

A few molecules and ions, such as oxygen, carbon dioxide, alcohol, caffeine, nicotine, and anesthetics, can move directly across the lipid bilayer of the cell membranes by diffusion. A few other substances are moved across the plasma membrane by highly selective transport proteins. The most significant of these transported molecules is glucose, which is the source of metabolic energy for the cells of the brain.

Imaging the Living Brain

Because the brain is encased in the skull, observing what happens inside it has historically been challenging. New technologies, however, enable us to indirectly observe the living brain by creating images without physically entering the skull. These technologies have become valuable tools in understanding how the brain functions. More importantly, these tools enable neuroscientists to understand and diagnose neurological diseases and disorders. Much has been learned about the functions of various brain regions by studying patients with brain damage caused by strokes, infections, tumours, and other conditions. Technologies such as functional magnetic resonance imaging (fMRI), 3-D ultrasound, and positron emission tomography (PET) allow researchers to identify the normal functions of specific brain regions in non-invasive ways. The instruments record a subject's brain activity during various mental and physical tasks by detecting minute increases in blood flow or metabolic activity in specific regions (**Figure 7**). CAREER LINK

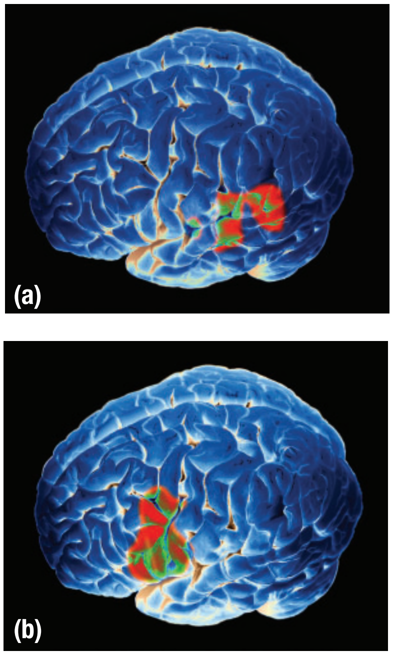


Figure 7 Areas of heightened neural activity are highlighted by different colours in this PET image of a living brain. Image (a) shows brain activity when hearing words. Image (b) shows brain activity when thinking about words.

Left Brain, Right Brain

Most of the other higher functions of the human brain, such as abstract thought and reasoning; the associations that form the basis of personality; spatial recognition; and mathematical, musical, and artistic ability, involve the coordinated participation of many regions of the cerebral cortex. Some of these regions are equally distributed in both hemispheres, and others are more concentrated in one hemisphere.

Among the functions that are more or less equally distributed between the two hemispheres is the ability to recognize faces. Consciousness, the sense of time, and recognizing emotions also seem to be distributed in both hemispheres. The left hemisphere specializes in spoken and written language, abstract reasoning, and precise mathematical calculations. The right hemisphere specializes in non-verbal conceptualizing, intuitive thinking, musical and artistic abilities, and spatial recognition functions such as fitting pieces into a puzzle. The right hemisphere also specializes in mathematical estimates and approximations that can be made by visual or spatial representations of numbers. Thus, in most people, the left hemisphere is verbal and mathematical, and the right hemisphere is intuitive, spatial, artistic, and musical.

The labels "left-brained" and "right-brained" are sometimes used when referring to someone's abilities. These labels can only be used loosely, however, to describe tendencies. While there is some measurable dominance of different functions on different sides of the brain, most productive functioning is integrated in both sides. There is no clear-cut division of functions, except that the right side of the body is controlled by the left side of the brain, and vice versa.

In the next section, you will explore the peripheral nervous system. As indicated by its name, this system links the periphery of the body with the central nervous system.

11.3 Review

Summary

- The central nervous system (CNS) consists of the brain and spinal cord. The spinal cord carries signals between the brain and the peripheral nervous system (PNS), and also controls reflexes.
- Cerebrospinal fluid provides nutrients to the CNS and cushions the CNS. A blood–brain barrier allows only selected substances to enter the cerebrospinal fluid.
- Grey-matter centres in the pons and medulla control involuntary functions, such as heart rate, blood pressure, respiration rate, and digestion. Centres in the midbrain coordinate responses to visual and auditory sensory input.
- The cerebellum integrates sensory input with visual and auditory signals to coordinate body movements.
- The primary somatosensory areas of the cerebral cortex register incoming sensory information. The primary motor areas of the cerebrum control voluntary movements of skeletal muscles in the body.
- The thalamus receives, filters, and relays sensory and motor information. The hypothalamus regulates basic homeostatic functions and contributes to endocrine control. The basal nuclei affect the planning and fine-tuning of body movements.
- Some functions, such as long-term memory and consciousness, are equally distributed between the two cerebral hemispheres. Other functions are concentrated in the left hemisphere or the right hemisphere.

Questions

1. What are the three main regions of the brain that are shared by all primates? What makes the human brain different? K/U
2. What are the main functions of the spinal cord? K/U
3. In a collision with an opposing player, a hockey player suffers damage to the cerebellum. How might this affect the player's body movements? K/U A
4. Which side of the brain controls which side of the body? What connects the two hemispheres? K/U
5. What does it mean to be "left-brained" or "right-brained"? K/U
6. One of the newest and most effective methods for scanning the brain is MEG, or magnetoencephalography. Use the Internet and other sources to research this technology. Prepare a brochure, based on your research, that includes the following information:
    - the underlying scientific principles of MEG
    - how and why it is used in neuroscience
    - the advantages and disadvantages of MEG, compared with other technologies T/I C
7. Bigger animals have bigger brains. Does this mean that bigger animals are smarter than smaller animals? Explain your answer. K/U T/I
8. A man suffers a stroke. He is unable to speak, but he can read and understand text. Explain how his brain has most likely been affected. K/U T/I
9. What is the function of the blood–brain barrier, and how does it accomplish this function? K/U
10. What are some techniques that are used today to study brain functions? K/U
11. Which part of the brain most likely evolved first: the brain stem or the cerebellum? Explain your reasoning. K/U T/I
12. Scientists have recently found a connection between sight and touch in the brain. Your brain not only processes what the object looks like, but remembers what it feels like to touch it as well. K/U T/I
    (a) Why do you think that the brain makes such a strong connection between the mind and touch?
    (b) How could this benefit you?

WEB LINK

The Peripheral Nervous System

11.4

The CNS works in close communication with the peripheral nervous system (PNS), which is the other main division of the nervous system. In humans, the PNS plays an important role in regulating both movement and the internal environment of the body.

As you may recall from Section 11.1, the nervous system is a set of systems within a system. The PNS is divided into two subsystems. The afferent system receives information from specialized cellular structures called receptors, and transmits this information to the CNS. The efferent system, on the other hand, carries signals away from the CNS to the muscles and glands. You will learn about the afferent system in Section 11.5, when you examine the senses. In this section, you will examine the roles of the various parts of the efferent system in maintaining normal body functioning and homeostasis.

Efferent System

The efferent system of the peripheral nervous system is made up of axons of neurons that carry signals to the muscles and glands, which act as effectors. The efferent system is subdivided into the somatic system, which communicates with the skeletal muscles, and the autonomic system, which communicates with the smooth muscles and glands.

Somatic System

The somatic system is mainly conscious and voluntary. It controls body movements and carries signals from the CNS to the skeletal muscles. It consists of 31 pairs of **spinal nerves**: 8 cervical, 12 thoracic, 5 lumbar, 5 sacral, and 1 coccygeal (**Figure 1**).

spinal nerves the 31 pairs of nerves within the somatic system that transmit motor, sensory, and autonomic signals between the spinal cord and the rest of the body

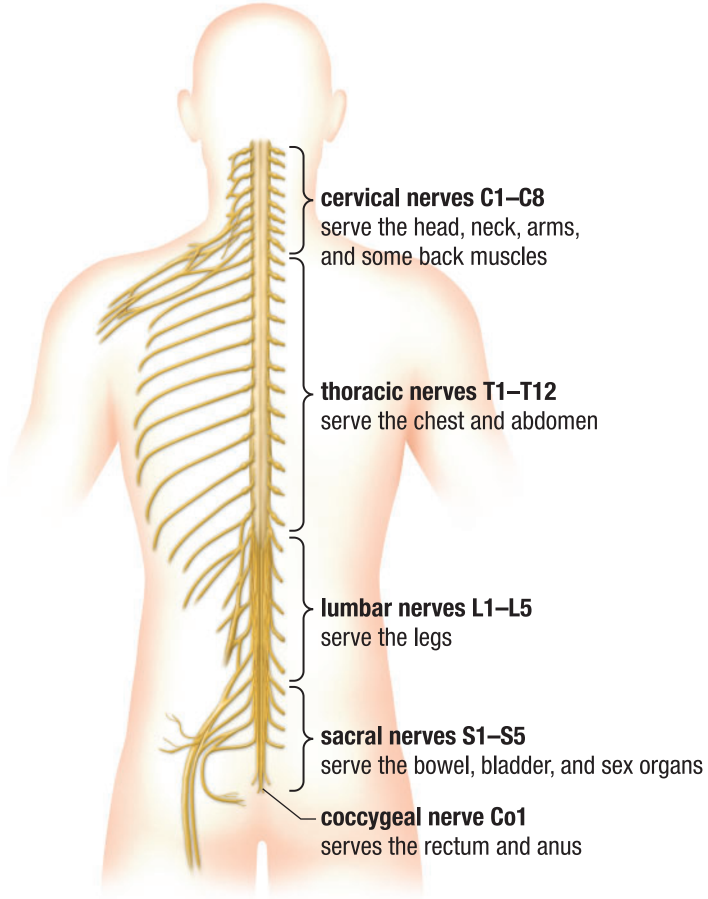

cervical nerves C1–C8
serve the head, neck, arms, and some back muscles
thoracic nerves T1–T12
serve the chest and abdomen
lumbar nerves L1–L5
serve the legs
sacral nerves S1–S5
serve the bowel, bladder, and sex organs
coccygeal nerve Co1
serves the rectum and anus

Figure 1 The 31 pairs of spinal nerves are grouped according to the area of the body that they serve.

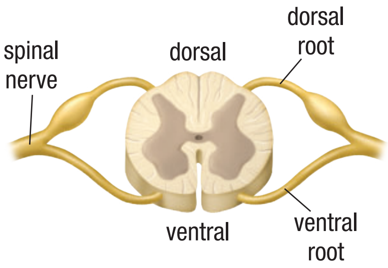


Figure 2 From each side of the spinal cord, a dorsal and a ventral root merge to form each of the 31 pairs of spinal nerves.

The spinal nerves emanate from the spaces between vertebrae and reflect the segmental organization of the vertebrate body. Each pair of spinal nerves serves a different part of the body. The cervical nerves serve the head and neck, the arms, and some back muscles. The thoracic nerves innervate the chest and abdomen. The lumbar nerves innervate the legs, and the sacral nerves serve the bowel, bladder, and sex organs. The coccygeal nerve serves the rectum and anus.

From the spinal cord, a dorsal root carries sensory information to the CNS and a ventral root relays motor information from the CNS (**Figure 2**). These roots merge to form a spinal nerve. The spinal roots, which lie outside the spinal cord, constitute the beginning of the PNS. At every level, from the bottom to the top of the spinal cord, one ventral and one dorsal root enter from each side of the body to form a spinal nerve. Each spinal nerve branches repeatedly so that nerves serve the entire body.

In mammals, motor neurons exit from the spinal cord in the ventral root to carry efferent signals from the CNS to the skeletal muscles. The dendrites and cell bodies of the motor neurons are located in the spinal cord. Their axons extend from the spinal cord to the skeletal muscle cells they control. As a result, the somatic portions of the spinal nerves consist only of axons.

Although the somatic system is primarily under conscious and voluntary control, some contractions of the skeletal muscles are unconscious and involuntary. These involuntary contractions include reflexes, shivering, and the constant muscle contractions that maintain body posture and balance.

Autonomic System and Homeostasis

The autonomic nervous system is the other subdivision of the efferent system. It works with the endocrine system to regulate the body in response to changes in its internal or external environment. The autonomic nervous system uses motor nerves to control largely involuntary processes, such as digestion, secretion by sweat glands, circulation of the blood, many functions of the reproductive and excretory systems, and the contraction of smooth muscles in all parts of the body. Normal breathing, for example, is rarely directed consciously. It is regulated by the autonomic nervous system in response to the level of circulating carbon dioxide and oxygen in the blood.

SYMPATHETIC AND PARASYMPATHETIC DIVISIONS

The autonomic nervous system is organized into sympathetic and parasympathetic divisions. These divisions are always active and have opposing effects on the organs they affect, thus enabling precise control (**Figure 3**, next page). In the circulatory system, sympathetic neurons stimulate the heartbeat, increasing its force and rate, while parasympathetic neurons inhibit the heartbeat. In the digestive system, sympathetic neurons inhibit the smooth muscle contractions that move materials through the small intestine, while parasympathetic neurons stimulate the same activities. A combination of these opposing effects allows involuntary body functions to be controlled precisely.

Each pathway in the autonomic nervous system uses two neurons. The dendrites and cell body of the first neuron are in the CNS, and its axon extends to a ganglion outside the CNS. A ganglion is an enlargement of the nerve where the cell bodies of neurons are located. There, its axon synapses with the second neuron in the pathway. The axon of the second neuron extends from the ganglion to the effector, which carries out the response. The sympathetic division is associated primarily with the nerves of the chest and abdomen. Just ventral to the vertebral column is a chain of ganglia (singular: ganglion). The ganglia are clusters of neuron cell bodies that connect the nerves to the CNS. The parasympathetic division has ganglia located within the brain, and the axons exit as cranial nerves or as the posterior or sacral parasympathetic nerves. The **cranial nerves** connect the brain directly to the head, neck, and body trunk. The sacral parasympathetic nerves innervate the lower digestive tract and the external genitalia.

cranial nerves the 12 pairs of nerves within the parasympathetic division of the autonomic system, which emerge directly from the brain and serve the head, neck, and body trunk

The sympathetic division predominates during situations that involve stress or excitement or during strenuous physical activity. Signals from the sympathetic division increase the force and rate of the heartbeat, raise the blood pressure, dilate the

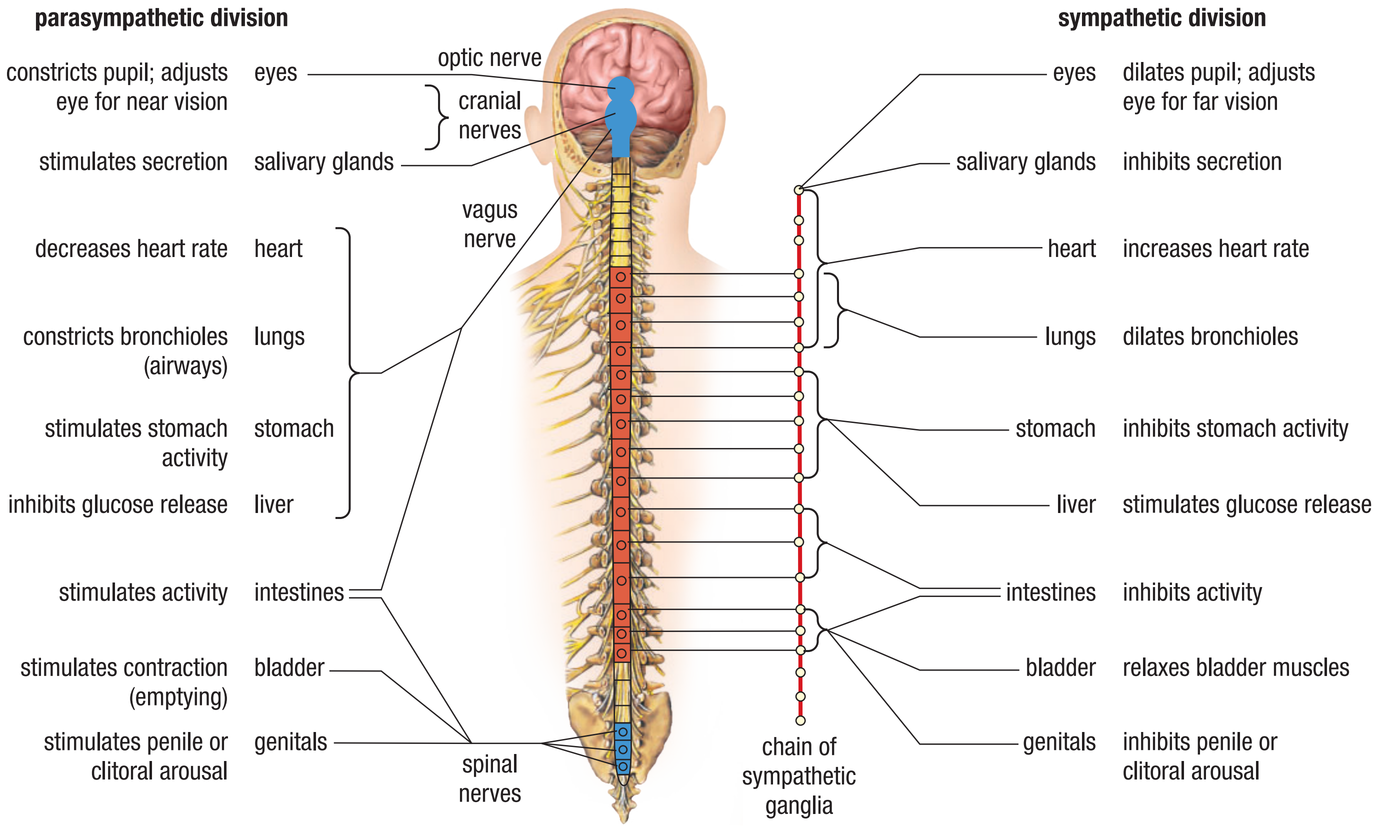


Figure 3 The autonomic system is divided into the sympathetic and parasympathetic divisions. These two divisions affect the functions of a variety of organs and glands. Only one side of each division is shown, since both divisions are duplicated on the left and right sides of the body.

air passages in the lungs, induce sweating, and open the pupils. Functions that are less important in an emergency, such as digestion, are suppressed. The parasympathetic division, in contrast, predominates during quiet, low-stress situations. Under its influence, the effects of the sympathetic division (such as rapid heartbeat and elevated blood pressure) are reduced and maintenance activities (such as digestion) predominate.

Pain and Painkillers

Everyone has experienced pain. Pain can come from a variety of sources—from a superficial scratch on the skin to the trauma of a broken leg to the pain of scalding or freezing water. Pain can vary in intensity from mild and barely noticeable to excruciating and incapacitating. In many cases, pain is short term and disappears in a few minutes, hours, or days. However, some conditions lead to chronic, long-term pain.

Pain is an interpretation by the brain of sensory input received by specialized cells known as the **substantia gelatinosa (SG)**. The SG forms a band in the dorsal horn of the grey matter in the spinal cord. Its name derives from its gelatinous appearance because most of the cells in this region are unmyelinated. Our perception of pain is caused when SG cells are stimulated by an afferent nerve of the peripheral nervous system (for example, when you stub your toe). The SG produces a neurotransmitter that communicates with the injured organ or tissue and relays a message to the brain, which interprets the message as pain. The brain then signals the release of natural painkillers known as endorphins and enkephalins (a class of chemicals called opioids). Neurotransmitters are produced by the pituitary gland and the hypothalamus during pain, excitement, exercise, and sexual intercourse, and even when eating spicy foods. They attach to the SG cell receptor sites and prevent communication with the injured organ or tissue. When the situation is painful, the perception of pain is diminished. When the situation is exciting, a feeling of euphoria develops.

substantia gelatinosa (SG) a band of grey matter in the spinal cord that, when stimulated, produces a neurotransmitter that communicates with an injured region of the body; a simultaneous signal to the brain results in the perception of pain

If you are a runner, or if you know someone who likes to run, you may be familiar with the phenomenon referred to as the "runner's high": a feeling of pleasure experienced during or after periods of intense exercise. When endorphins or enkephalins are released during exercise, they attach to SG receptor sites. The pleasurable sensation that runners experience is actually the reduction of pain.

While the popular belief in the runner's high dates back many decades, it was only in 2008 that German researchers were able to scientifically test the hypothesis that an endorphin-driven runner's high actually exists. Using brain imaging, they were able to show that running for 2 h increased the release of endorphins in specific regions of the brain. In their study, 10 athletes had a PET (positron emission tomography) scan before and after a long-distance run. The researchers used a radioactive marker to examine the binding of naturally produced painkillers on the brain's opioid (painkiller) receptors. By comparing the before and after images, the researchers detected that the body increased its production of opioids, and they were able to identify the affected brain areas.

Because of this effect on mood, it is perhaps not surprising that many studies have found a link between exercise and clinical depression. Several studies have suggested that exercise may be just as effective as antidepressant medications for treating depression. Different types of exercise appear to be equally effective, but what dose of exercise is enough is still the subject of investigation. Nevertheless, a growing body of evidence for the efficacy of exercise in the treatment of major depressive disorders has led some Canadian physicians to suggest that it should be the first line of treatment for depression.

Synthetic painkillers use the same mechanisms as naturally produced endorphins and enkephalins (**Figure 4**). Opioids, such as heroin, codeine, and morphine, attach to SG neurons within the CNS, preventing pain transmitters from being produced. Opium and heroin also induce a feeling of calm. The use of opioids causes the body to reduce its production of natural painkillers. Thus, the drug must be taken continuously to experience a constant effect.

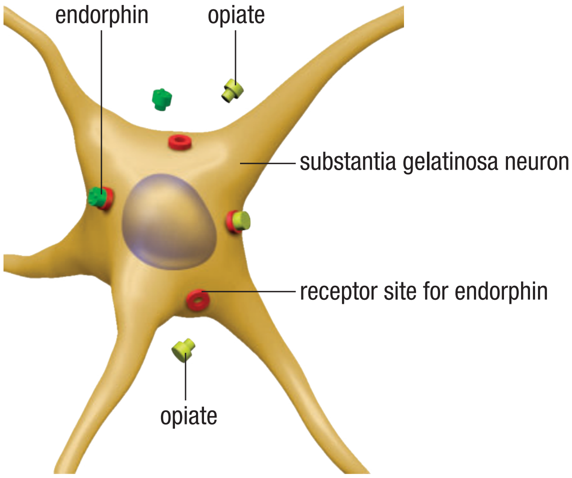


Figure 4 Synthetically produced opiates are structurally similar to endorphins. The similarity in structure allows these drugs to bind to the SG receptor sites that would naturally host the binding of endorphins.

Opioid drugs are often associated with substance abuse and dependence. Opium is so named because it is derived from the milky sap of the unripened seedpod of the opium poppy. Opium has been used as a painkiller for several thousand years, and it is still cultivated for both legitimate and illegitimate purposes, mainly in Myanmar and Afghanistan. While opium and its derivatives are effective for treating chronic pain, their highly addictive properties often present physicians with a dilemma: Is the relief of pain worth the risk of creating physical dependency and possible addiction to a drug?

11.4 Review

Summary

- Signals from the central nervous system travel, via efferent neurons, to the muscles and glands that carry out appropriate responses.
- The somatic system of the peripheral nervous system (PNS) controls the skeletal muscles that produce voluntary body movements, as well as the involuntary muscle contractions that maintain balance, posture, and muscle tone.
- The autonomic system of the PNS controls involuntary functions, such as heart rate, blood pressure, glandular secretions, and smooth muscle contractions.
- The autonomic system is organized into sympathetic and parasympathetic divisions, which balance and fine-tune involuntary body functions. The sympathetic system predominates in situations of stress, danger, or strenuous activities. The parasympathetic system predominates during quiet, low-stress situations.
- Naturally produced painkillers (such as endorphins and enkephalins) and synthetic painkillers (such as opium, morphine, and heroin) work because they block or reduce the binding of pain neurotransmitters to substantia gelatinosa (SG) receptor cells.

Questions

1. Use a graphic organizer or a written format to compare and contrast the following divisions of the nervous system: K/U C
   (a) the somatic and the autonomic divisions of the nervous system
   (b) the sympathetic and parasympathetic divisions of the autonomic system
2. How does the dorsal root of the spinal cord differ from the ventral root? K/U
3. Explain the mechanism by which endorphins relieve pain. K/U
4. Why might exercise affect mood and be useful for the treatment of clinical depression? Discuss your ideas with a partner, and explain your reasoning. K/U C A
5. Why do you think the severity of a spinal cord injury depends on the location where the spinal cord was severed? K/U A
6. Explain how the fight-or-flight response activates both the sympathetic and parasympathetic nervous systems. K/U
7. Compare and contrast the functions of the types of neurons found in the peripheral nervous system and the central nervous system. K/U
8. Compare and contrast endorphins and enkephalins. K/U
9. In 1996, a team from the Institut Pasteur in Paris discovered opiorphin, an endogenous chemical compound, first isolated in saliva, that modulates the half-life of enkephalins. Its discovery opened a new window for the development of natural painkillers. Using the Internet and other sources, find out more about opiorphin. Write a paragraph explaining its potential use as a natural painkiller. T/I C
10. A mnemonic often used to remember the cranial nerves is the following: On Old Olympus's Towering Tops A French And German Viewed Some Hops. The first letter of each word corresponds to a cranial nerve. Use the Internet and other sources to research the names of the 12 pairs of cranial nerves. Create and share in poster format a new mnemonic to help you and your classmates memorize the 12 pairs of cranial nerves in the correct order. K/U C
11. A young athlete falls while skateboarding and lands on the left side of his head. He recovers from his injury with the exception of the following symptoms: his left eyelid droops, his left pupil is dilated, he experiences loss of near vision in the left eye, and he cannot move the left eyeball downward and outward. Use the Internet and other sources to research the cranial nerves. Which of the cranial nerves do you think is or are most likely damaged? Briefly explain your reasoning. T/I

WEB LINK

11.5 The Senses

Humans do not have the acute sensory abilities of some other animals. For example, we cannot detect very low concentrations (for example, in ppm) of illegal drugs or explosive chemicals the way that some pigs can. Nor can we hear the high-frequency sounds that dogs can hear, or see the infrared portion of the electromagnetic spectrum that rattlesnakes can "see." However, the combination of all of our senses enables us to observe and respond to our environment successfully.

Toothed whales, dolphins, many bats, some birds, and some insectivorous mammals have the ability to locate objects through echolocation. Echolocation is the transmission of a sound and the interpretation of the sound that is reflected as an echo (**Figure 1**). This specialized adaptation allows some animals to navigate in environments where visibility is limited.

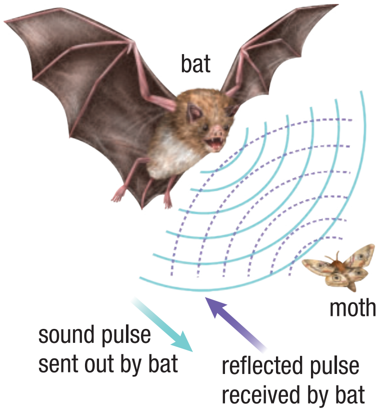

bat
moth
sound pulse sent out by bat
reflected pulse received by bat

Figure 1 To capture a flying insect, a bat transmits a pulse of sound and then interprets the reflected pulse to determine the location of the insect.

Scientists have long assumed that humans are incapable of echolocation. Recently, however, neuropsychologists at the University of Western Ontario's Centre for Brain and Mind and Toronto's Rotman Research Institute have used functional magnetic resonance imaging (fMRI) to investigate the abilities of people who are blind and have learned to echolocate. Daniel Kish, a man in his 40s who lost his sight at 13 months of age, cannot recall a time when he did not use vocal clicks to navigate. His parents noted that he began to make clicking sounds at about 18 months of age. Based on fMRI images, scientists have learned that the part of the brain that processes visual input in sighted people (the visual cortex) becomes active when echolocation is used. In this section, you will explore the five senses of sight, hearing, taste, smell, and touch to understand how we acquire and use information from our internal and external environments.

Information Input

In Section 11.4, you learned about the efferent system of the PNS. You will now learn about the afferent system of the PNS, whose receptors sense stimuli outside or on the surface of the body and send information to the CNS. There are five types of sensory receptors that receive stimuli and send information to the CNS:

- Mechanoreceptors detect mechanical energy, such as changes in pressure, body position, or acceleration. Auditory receptors in the ears are mechanoreceptors.
- Photoreceptors detect the energy of light. In vertebrates, photoreceptors are mainly located in the retina of the eye.
- Chemoreceptors detect specific molecules or chemical conditions, such as acidity. Taste buds on the tongue are examples of chemoreceptors.
- Thermoreceptors detect the flow of thermal energy. These receptors are located in the skin, where they detect changes in the temperature of the body surface.
- Nociceptors, or pain receptors, detect tissue damage or noxious chemicals. Their activity registers as pain. Nociceptors are located in the skin and in some internal organs.

Some animals also have receptors that detect electrical or magnetic fields. Songbirds, for example, can use the detection of Earth's magnetic field as one method of orientation during migration. Traditionally, humans are said to have five senses: vision, hearing, taste, smell, and touch. In reality, we can detect almost twice as many kinds of environmental stimuli. We can also detect external thermal energy; internal temperature; gravity; acceleration; internal pH; and the internal concentrations of substances such as oxygen, carbon dioxide, salts, and glucose. Some of the receptors that play a role in these senses are associated with the autonomic nervous system.

Sensory receptors are not evenly distributed throughout the body. Some parts of the body, such as the lips and fingers, have many more touch receptors per unit area and are therefore more sensitive than other parts of the body. Some sensory receptors, such as touch receptors, are positioned individually in body tissues, while others are part of complex sensory organs, such as the eyes or ears. Sensory organs, particularly those that receive external stimuli, such as the eyes, ears, and antennae, usually occur in pairs.

In many sensory systems, the effect of a stimulus is reduced if it continues at a constant level. This reduction is called **sensory adaptation**. Some receptors adapt quickly and broadly, but others adapt only slightly. For example, when you get into bed, you are initially aware of the touch and pressure of the covers on your skin. Within a few minutes, however, the sensations lessen or are lost, even though you are still under the covers.

sensory adaptation the tendency for some sensory receptors to become less sensitive when stimulated repeatedly

In some sensory receptors, biochemical changes in the receptor cells contribute to adaptation. When you move from a dark movie theatre into the bright sunshine, the photoreceptors in your eyes adapt to the sudden bright light, partly through the breakdown of some of the pigments that absorb light. Sensory adaptation is crucial to survival. Adaptation of the photoreceptors in our eyes keeps us from being blinded indefinitely as we pass from the dark into bright sunlight. Sensory adaptation also increases the sensitivity of receptor systems to changes in environmental stimuli.

In contrast, receptors that detect painful stimuli show little or no adaptation. Pain detectors are essential for survival. They signal a potential danger to some part of the body, and they maintain the signal until a response by the animal compensates for the stimulus causing the pain.

The Traditional Senses

The role of the five traditional senses (vision, hearing, taste, smell, and touch) is to enable us to receive information about our external environment. What is their role in the afferent part of the PNS, and how do they connect to the CNS?

Vision

Vision is probably the most complex of the five traditional senses in humans. Photoreceptors in the retina, located at the inside rear of the eye, detect light at particular wavelengths. They convert the light stimuli to nerve impulses, which move the information via the optic nerve to visual centres in the brain. The human eye has a lens that forms images (**Figure 2**) and then focuses the images on the field of photoreceptors, which convert the signals from electromagnetic energy to nerve impulses. Signals that originate at the photoreceptors are integrated in the brain into a point-by-point representation of the viewed object. The retina holds layers of neurons that perform an initial integration of visual information before it is sent to the brain. There are two types of photoreceptors in the retina: rods and cones (**Figure 3**). Rods are specialized for the detection of light at low intensities. Cones are specialized for the detection of different wavelengths (colours). The retina of a human eye contains about 120 million rods and 6 million cones, organized into a densely packed single layer.

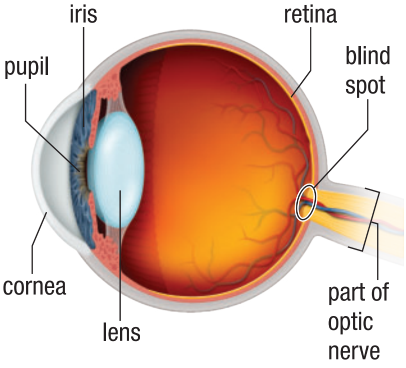


Figure 2 The major structures in the human eye

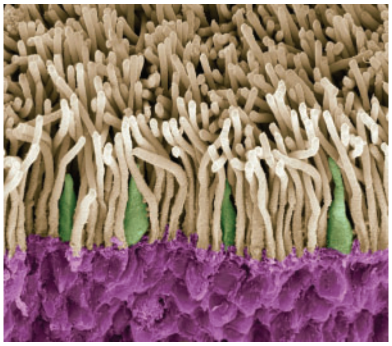


Figure 3 A scanning electron micrograph of the rods (white) and cones (green) of the eye

Hearing

The auditory organ for humans is the ear. The pinna (outer ear) focuses sound waves. Inside the auditory canal, sound waves strike a thin sheet of tissue, called the tympanic membrane or eardrum, causing it to vibrate. These vibrations generate vibrations in the auditory ossicles, the chain of tiny bones located in the air-filled middle ear. Mammal ears have three auditory ossicles: the malleus (hammer), the incus (anvil), and the stapes (stirrup) (**Figure 4**, next page). The stapes meets the inner ear at the oval window. The oval window is a thin, elastic membrane, where vibrations in bone are converted to vibrations in fluid in the cochlea.

The inner ear contains several fluid-filled compartments: the semicircular canals (which enable us to keep our balance and be aware of our body position) and a spiral tube called the cochlea. The vibrations in the fluid cause vibrations in the basilar membrane, which forms part of the floor of the cochlea and anchors the sensory

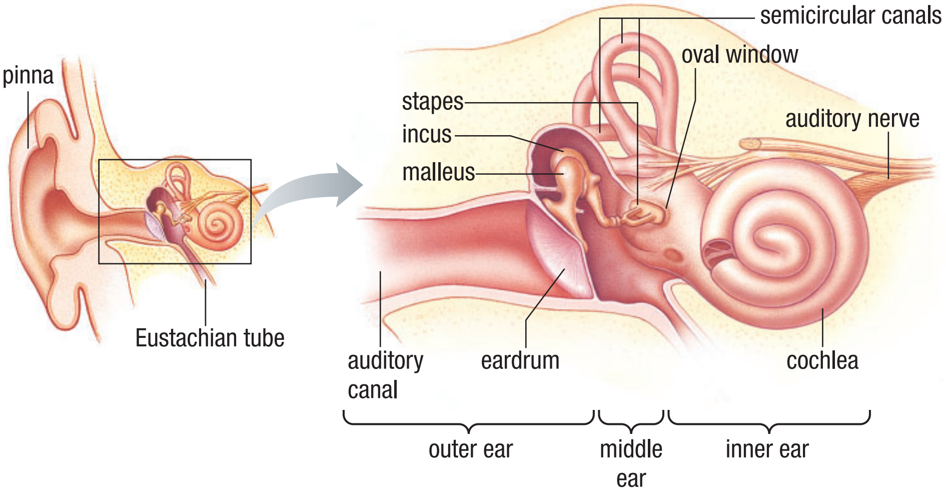


Figure 4 The internal structures of the outer, middle, and inner parts of the human ear

hair cells. Vibrations of the basilar membrane cause the hair cells to bend. This stimulates them to release a neurotransmitter that triggers action potentials in afferent neurons leading from the inner ear. Each frequency of sound waves causes hair cells in a different segment of the basilar membrane to initiate action potentials. There are more than 15 000 hair cells, which are connected to afferent neurons. The axons of the afferent neurons are bundled together in the auditory nerve, leading to the thalamus. Signals are routed from the thalamus to the auditory centre of the temporal lobe, where they are interpreted as sounds.

A duct called the Eustachian tube leads from the air-filled middle ear to the throat. The Eustachian tube protects the eardrum from damage caused by changes in environmental atmospheric pressure. As you swallow or yawn, the Eustachian tube opens, allowing air to flow into or out of the middle ear. This equalizes the pressure on both sides of the eardrum.

Taste and Smell

Chemoreceptors are receptors that are involved in taste and smell. They also sense levels of oxygen, carbon dioxide, and hydrogen ions in the body. All chemoreceptors probably work through membrane receptor proteins that bind with specific molecules in the environment. Taste receptors form part of a structure called a taste bud, which is a small pear-shaped capsule with a pore that opens to the exterior at the top (**Figure 5**). The sensory hairs of taste receptors pass through the exterior pore of a taste bud and are exposed to the inside of the mouth. The opposite ends of the receptor cells synapse with the dendrites of an afferent neuron.

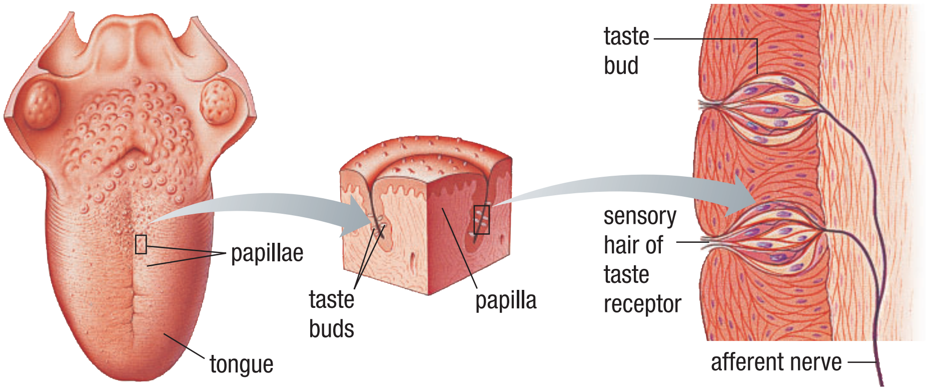


Figure 5 Chemoreceptors on the human tongue are found in structures known as taste buds.

Humans have about 10 000 taste buds, each 30 to 40 μm in diameter. The taste buds are scattered over the tongue, the roof of the mouth, and the throat. The taste buds on the tongue are embedded in outgrowths called papillae (from *papula* meaning "pimple"), which give the tongue its rough texture. Taste receptors on the human tongue respond to five basic tastes: sweet, sour, salty, bitter, and umami (savoury).

Signals from taste receptors are relayed to the thalamus. From there, some signals travel to gustatory or taste centres in the cerebral cortex, which interpret them as different tastes. Some signals travel to the brain stem, which links tastes to involuntary visceral and emotional responses. A pleasant taste may lead to salivation, the secretion of digestive juices, and sensations of pleasure. An unpleasant taste may produce nausea and vomiting.

Each olfactory receptor cell has 10 to 20 sensory hairs, which project into a layer of mucus that covers the olfactory area in the nose. To be detected, airborne molecules must dissolve in the watery mucus. Olfactory receptors are distinct among sensory receptors because they make direct connections with brain interneurons, rather than making connections via afferent neurons. Nerves from olfactory bulbs conduct signals to the olfactory centres of the cerebral cortex, where they are interpreted as tantalizing or unpleasant odours. As with taste, some olfactory bulbs also connect to the brain stem, where nerve signals elicit emotional and visceral responses similar to those caused by different tastes.

Touch

In vertebrates, mechanoreceptors that detect touch and pressure are embedded in the skin and other surface tissues, in the skeletal muscles, in the walls of blood vessels, and in the internal organs. The mechanical forces of a stimulus distort proteins in the plasma membrane of receptors, altering the flow of ions through the membrane. Ion flows change the membrane potential of the receptors and generate action potentials in afferent neurons leading from the receptors to the CNS.

Human skin contains several types of touch and pressure receptors (**Figure 6**). Free nerve endings are dendrites of afferent neurons with no specialized structures surrounding them. In Pacinian corpuscles, structures surrounding the nerve endings contribute to the reception of stimuli. Free nerve endings wrapped around hair follicles respond when the hairs are bent, making us instantly aware of a light touch.

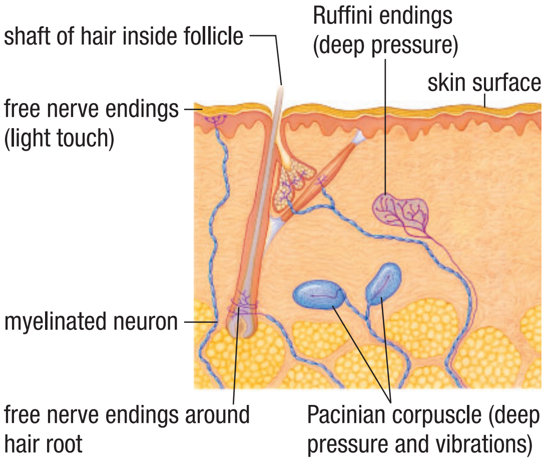

shaft of hair inside follicle
Ruffini endings (deep pressure)
skin surface
free nerve endings (light touch)
myelinated neuron
free nerve endings around hair root
Pacinian corpuscle (deep pressure and vibrations)

Figure 6 Mechanoreceptors detect tactile stimulation (touch) in human skin.

The touch receptors in human skin are concentrated in the fingertips and lips, and on the tip of the tongue, giving these areas the greatest sensitivity to mechanical stimuli. In other areas, such as the skin of the back, arms, and legs, the receptors are more widely spaced.

Thermoreceptors, Thermoregulation, and Pain

As already mentioned, there are more than five senses. Most animals have thermoreceptors, which can detect changes in the temperature of their surroundings. Some snakes, such as pit vipers, use a pair of pit organs (thermoreceptors) located in depressions just below each eye to detect infrared radiation (thermal energy). This enables them to detect the body thermal energy of endothermic prey, such as mice and other small mammals (**Figure 7**).

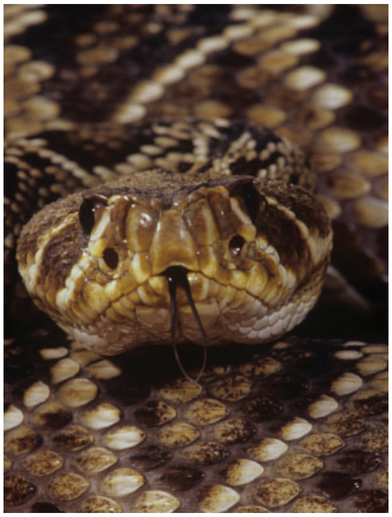


Figure 7 The pit organs of an eastern diamondback rattlesnake are located in depressions on both sides of the head, below the eyes.

In mammals, distinct thermoreceptors respond to hot and cold. Three kinds of Ca^{2+} channels act as thermoreceptors. One responds when the temperature reaches 33 °C, and another responds when the temperature goes above 43 °C and starts to be painful. Both receptors probably play a role in thermoregulation. A third receptor responds at temperatures of 52 °C and above, producing only a pain response. This receptor is not believed to be involved in thermoregulation. Two cold receptors are also found in mammals. One responds between 8 and 28 °C and probably plays a role in thermoregulation. The second responds to temperatures below 8 °C and appears to be associated with pain rather than thermoregulation. The mechanisms that control the opening and closing of hot and cold receptor channels are not currently known.

Thermoreception in humans is performed by several specialized receptors. Some neurons in the hypothalamus of mammals function as thermoreceptors, sensing changes in brain temperature and receiving afferent thermal information. They are sensitive to shifts from normal body temperature and trigger involuntary responses, such as sweating, panting, or shivering, which restore normal body temperature. Maintaining the human body at normal body temperature (about 37 °C) is important for numerous processes. Temperatures that are too high or too low can cause serious complications, including impeded nerve transmission, irregularities in heart rate, internal bleeding, organ damage, and cell death.

Free nerve endings (branched endings of sensory neurons) are the simplest type of thermoreceptors. They are either unmyelinated or thinly myelinated, and they adapt slowly to stimulation by thermal energy. Ruffini endings, which are located deep within the skin, are another type of slowly adapting receptor. Ruffini endings respond to temperatures above 45 °C, and also to touch and pressure. Closer to the surface of the skin, another type of thermoreceptor is activated at temperatures of 20 °C or lower. When this type of receptor senses a temperature below 10 °C, it alerts the body to cold through a pain response. Anyone who has experienced frostbite can attest to the pain response caused by extreme cold.

In **Figure 8**, you can see the flushed face that results as body temperature is elevated by exercise. The change in body temperature is detected by thermoreceptors and then transmitted and interpreted by the hypothalamus, which sends out a signal to dilate the blood vessels in the skin. This increases the blood flow near the skin, increasing the transfer of thermal energy to the air, which cools down the body. Local nerves also stimulate vasodilation of the blood vessels in the skin by the release of a neurotransmitter known as substance P (a calcitonin gene–related peptide neurotransmitter). Capsaicin, the characteristic ingredient in hot peppers, triggers this same response, causing the local sensation of heat and vasodilation in the skin.

Figure 8 The red flushed face during physical exertion is caused by the dilation of blood vessels in the surface of the skin, an attempt to cool the body by releasing thermal energy to the air.

Pain receptors, called nociceptors, detect damaging stimuli, which are interpreted by the brain as pain. Pain is a protective mechanism that prompts animals to do something to remove or decrease the damaging stimulus immediately. Often pain elicits a reflex response, such as withdrawing the hand from a hot stove, which occurs before we are consciously aware of the sensation. Whereas many sensory receptors aid in normal homeostasis, pain receptors respond to more serious and potentially damaging internal or external conditions. Pain receptors are the most numerous type of sensory receptor. For each square centimetre of skin, there are around 200 pain receptors, 15 pressure receptors, 6 cold receptors, and 1 heat receptor.

Mechanical damage, such as a cut, pinprick, or blow to the body, can cause pain. Some nociceptors are specific for a particular type of damaging stimulus, whereas others respond to more than one type of stimulus. Axons that transmit pain signals are part of the somatic system of the PNS. They synapse with the interneurons in the grey matter of the spinal cord and activate neural pathways to the CNS by releasing the neurotransmitters glutamate and/or substance P. Glutamate-releasing axons produce sharp, prickling sensations that can be localized to a specific body part, such as the pain of stepping on a tack. Substance P–releasing neurons produce dull, burning, or aching sensations that are not easily localized, such as the more widespread pain when you stub your toe.

As part of their protective function, pain receptors adapt very little, if at all. Some pain receptors increase the rate at which they produce action potentials if the stimulus continues at a constant level. The CNS also has a pain-suppressing system. In response to stimuli such as exercise, hypnosis, and stress, the brain releases endorphins. Endorphins are natural painkillers that bind to membrane receptors on substance P neurons, reducing the amount of neurotransmitter released.

Investigation **11.5.1**

Exploring the Senses (p. 556)
You have learned how we use the senses to acquire information from our internal and external environments. In this investigation, you will observe particular senses to understand how sensory receptors of the nervous system help you to perceive your external environment.

Sensory Disorders

Some sensory disorders interfere with the reception, transmission, or processing of sensory stimuli. For example, a physical injury to an eye, an ear, or a spinal nerve may prevent the reception of the sensory stimuli or interfere with the transmission of signals from sensory receptors to the brain. This can result in the impairment or loss of a particular sense, as in the case of blindness from damage to the retina.

A sensory processing disorder (SPD), also known as a sensory integration disorder, manifests itself as difficulties in interpreting information from sensory receptors. Stimuli are received normally, but they are interpreted abnormally. Individuals with a sensory processing disorder may experience problems in one or more senses: touch, hearing, sight, taste, smell, vestibular (movement and gravity), or proprioceptive (body awareness). People who have SPD may experience hypersensitivity (over-stimulation) or hyposensitivity (under-stimulation).

SPD is often diagnosed in childhood. Children who have SPD have a different sensory perception of the world. For example, normal clothing may feel like sandpaper, and lights in a classroom may seem so bright that they burn the eyes. This disorder interferes with everyday functioning and causes great stress. Research is still ongoing but suggests that SPD has both genetic and environmental components. SPD is not curable, but occupational therapy can help to lessen some of the symptoms and their effects.

UNIT TASK **BOOKMARK**

Depending on the case study you choose to develop, you may be able to apply what you learned in this section about sensory disorders to the Unit Task described on page 566.

Research This

Sensory Processing Disorder

Skills: Researching, Communicating

SKILLS HANDBOOK A4.1

Sensory processing disorder (SPD) is the name given to a disorder in which sensory signals are not interpreted properly and do not elicit appropriate responses.

1. Use the Internet and other sources to research this disorder. Use the following questions as a guide for your research:
    - What is SPD? How common is this disorder?
    - How is SPD diagnosed?
    - What are the symptoms of SPD?
    - What are the implications for people who suffer from SPD?
    - What are the treatments for SPD?
    - What research about SPD is currently underway?

A. Describe three examples of specific sensory processing disorders. T/I

B. Why is SPD often misdiagnosed? T/I

C. Although much is known about SPD, there are gaps in our knowledge. What puzzles researchers the most about this disorder? T/I

D. Present a report of your findings in the form of a one-page magazine article (500 words or less), a 2 to 5 min radio documentary, a 2 to 5 min television news story, or a 5 min slide presentation. T/I C

WEB LINK

11.5 Review

Summary

- In the visual system, photoreceptors detect light stimuli at particular wavelengths. They convert the stimuli to nerve impulses, which move the information via the optic nerve to visual centres in the CNS.
- Hair cells in each ear sense sound and respond by triggering action potentials, sending signals via the auditory nerve to the thalamus and then to the brain's temporal lobe.
- Chemoreceptors for taste have receptors in taste buds that relay signals to the thalamus and then to gustatory (taste) centres, such as those in the cerebral cortex. Chemoreceptors for smell make direct connections with interneurons in the brain, rather than using afferent neurons as a conduit.
- Mechanoreceptors for touch and pressure are embedded in the skin and other surface tissues. They use changes in ion flow across their plasma membrane to generate action potentials in afferent neurons. These action potentials carry signals to the CNS.
- Other sensory abilities are involved in homeostasis, such as the ability to sense thermal energy, gravity, acceleration, internal pH, O_2, CO_2, salts, and glucose.
- Some sensory systems become less reactive to a stimulus if it continues at a constant level. This reduction is called sensory adaptation.
- When the body is subjected to potentially damaging internal and external conditions, nociceptors (pain receptors) detect these damaging stimuli and send a message to the brain that is interpreted as pain.
- A sensory processing disorder (SPD) is a neurological disorder that causes difficulties in processing information received from sensory receptors. Stimuli are received normally but are perceived or interpreted abnormally.

Questions

1. What is the importance of sensory systems for an organism? K/U
2. Name five sensory receptors and the type of stimulus that each detects. K/U
3. Why is it important that some receptors allow the effect of a stimulus to be reduced? K/U A
4. Why is it important that pain receptors do not undergo sensory adaptation? K/U
5. What do thermoreceptors and nociceptors have in common? K/U A
6. What are the three thermoreceptors that are found in humans? K/U
7. It has been claimed that spicy foods, especially those that contain capsaicin, can be addictive. Research this topic in detail, either on your own or in research teams or pairs. Determine why, in theory, a person might become addicted to spicy foods. Present your findings in a short (5 min or less) classroom presentation, in a format of your choice, using images as well as text if you wish. K/U T/I C A
8. The Eustachian tube maintains a balance of air pressure on both sides of the eardrum. How is the Eustachian tube important when flying or diving? How might a cold or infection affect the functioning of the Eustachian tube? K/U A

WEB LINK

The Body and Stress

11.6

Stress. We have all felt it. It happens when we get nervous or anxious. Think about when you have experienced stress. How did your body respond? If you are like most people, your hands started to sweat, your heart rate began to race, and your breathing quickened. Stress can also happen over longer periods of time, perhaps caused by the pressure of a demanding job, but the short-term symptoms do not occur.

In addition to emotional stress, the body responds to physical stress brought on by demanding activities, such as long-distance running (**Figure 1**). Distance runners push themselves through fatigue to finish a race. Their bodies experience enormous physical stress (and usually emotional stress as well, if they are in a race). In this section, you will explore what causes stress and how the body handles stress, including the symptoms; the effects on the body; and the responses by the nervous system, excretory system, and endocrine system.

Figure 1 Extreme fatigue from running a marathon can cause a stress response in the body. Removing the stressor and resting will allow the body to recover.

What Is Stress?

When your body is in a state of homeostasis, you are relaxed and exhibit no signs of stress. Stress is the body's response to a stimulus, or stressor, that triggers a move away from homeostasis. Although the word "stress" has negative connotations, stress can also be neutral or positive. The ongoing internal adjustments that maintain homeostasis are responses to stress, and, even though we are usually unaware of them, the effects are neutral. The extreme reactions of people who win contests and the reactions of people in love are examples of positive stress. Although the responses to stress can feel uncomfortable, they protect the body from an internal or external threat.

In the short term, negative stress is not necessarily harmful. Some types or degrees of stress can be beneficial because they cause the body to adapt to changing situations. Chronic and repeated stress, however, can harm the body. Symptoms of stress include an increase in respiration rate and heart rate, muscle tension, frequent urination, irritability, tiredness, and trouble sleeping. During stress, the body reduces blood flow to some organs (for example, those of the gastrointestinal tract), while blood flow to the brain and skeletal muscles increases. People who are stressed may have an upset stomach or a headache. Their hands may shake, and they may perspire more than normal.

The amount of stress that a person experiences depends on factors such as the duration and intensity of a stressor, as well as its predictability and controllability. To some degree, however, stress is subjective; that is, different people cope with the same situation in different ways. One person may exhibit few signs of stress in a situation that could cause another person extreme stress. A roller coaster may be scary for one person and thrilling for another. A death in the family may be devastating for one person, but another person may be better able to cope with the grief.

Our understanding of stress and its effects on the body owes much to the work of Hans Selye, a Canadian who was a pioneer in the field of endocrinology (**Figure 2**). Selye conducted a scientific study of stress from the 1940s to the 1970s and helped to found the Canadian Institute of Stress in 1979. His work established that stress is more than just an emotional response to the general environment; rather, it involves a biological response that can be clearly identified and described. He differentiated between bad stress, which he called "distress," and good stress, which he called "eustress."

Early in his work, Selye described the body's response to stressors in terms of what he called the general adaptation syndrome, which consists of three stages. In the first stage, the alarm reaction, the body mounts a fight-or-flight response, displaying the typical reactions to stress already mentioned. In the second stage, resistance, the body attempts to deal with the stress. If the stress stops, the body normalizes. If the stress continues, the body adapts to it, but sometimes at great cost. The resistance stage cannot continue indefinitely because it taps resources that become depleted. In the third stage, exhaustion, the body's resources are depleted and body function is impaired, sometimes to the point of death.

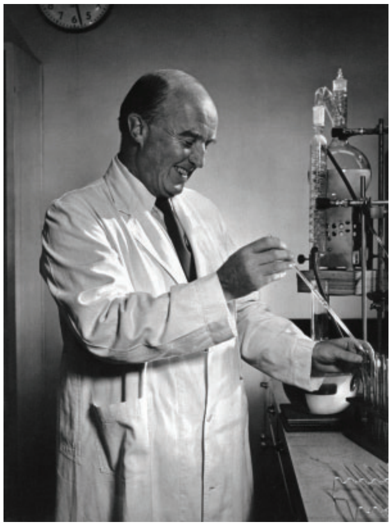


Figure 2 Canadian endocrinologist Hans Selye dedicated his working life to understanding how stress affects the body.

Causes of Stress

Stress can be physical, or psychological and emotional. If you become scared, you will probably have a fight-or-flight response. This puts your body on high alert, preparing you to react. You may also exhibit stress if you are resisting doing something that you want to do. Another type of stress comes with physical effort, such as long-distance running. Your body eventually becomes very fatigued. This is an example of extreme physical stress, but a stress that is easily ended when you halt the stressful activity.

Long-term stress can be caused by stimuli that occur again and again. A hectic and high-pressure job, for example, can cause psychological and emotional stress on a daily basis. Stress can also linger after a traumatic experience, such as being in a car accident or, for soldiers, being in combat. Even though the stressor has been removed, the person may exhibit post-traumatic stress disorder, a serious anxiety disorder that persists after a traumatic event is over. If long-term stress is not relieved, it can affect body systems in negative ways. Whatever the stressor, the personal nature of stress and the different ways people react to stress make it hard to recognize and define.

How Stress Affects the Body

Researchers are learning more and more about the interactions that create a stress response and ways that stress affects our bodies. Brief periods of stress have temporary effects on the body. Telltale responses, such as a racing heart rate, sweaty hands, and rapid breathing, are initiated by the nervous system, which stimulates action by certain hormones that ready the body for action, as shown in **Table 1**. Increases in blood glucose and heart rate, for example, ensure that the body has enough energy during times of stress.

Table 1 Hormones Involved in Stress Responses

Stress hormones	Responses in body
epinephrine and norepinephrine	promotes the conversion of glycogen to glucose and the conversion of fats to fatty acids to increase energy supply, making the muscles ready to respond if needed
cortisol	promotes the conversion of amino acids to glucose and the conversion of fats to fatty acids, increases blood glucose and fatty acids, and speeds up breathing and heart rate
glucagon and insulin	glucagon converts glycogen to glucose to increase the blood sugar level; decreased production of insulin also increases blood sugar level
antidiuretic hormone (ADH)	causes retention of water to increase blood pressure

Recall from Section 10.2 that the adrenal medulla secretes two hormones, epinephrine and norepinephrine, that are essential in the body's response to stress. Epinephrine, commonly known as adrenaline, prepares the body for the fight-or-flight response by increasing the heart rate, mobilizing energy stores, dilating blood vessels in the skeletal muscles, and opening the airways for better air flow. Norepinephrine has some of the same effects as epinephrine, but it also increases blood pressure and affects the amygdala, one of the attention centres in the brain.

Problems arise when the body experiences stress for a long period of time. Sustained increases in heart rate and blood glucose can have negative health effects. For example, long-term stress has been associated with high blood pressure and heart attacks. Stress can weaken the immune system, making the body vulnerable to illness. It can cause rashes or hives. Chronic stress is associated with stomach and intestinal problems, as well as sleep disorders and depression. The effects of stress are not completely understood, but they do seem to be far reaching.

Scientists who investigate stress are constantly learning more about how stress affects the body, hoping to find ways to minimize these effects before they do damage. For example, researchers at the University of Western Ontario announced in 2010 that they had discovered a link between cortisol levels in hair and the risk of having a stress-related heart attack. Cortisol is a stress hormone captured in the hair shaft. Measuring the cortisol levels in a 6 cm length of hair can reveal periods of high stress over six months. According to the study, higher than normal cortisol levels were found in the hair of heart attack patients in the three months before the attack. Scientists hope that one day this information will be helpful in identifying people who are at risk for stress-induced heart problems.

Stress is a significant concern within the teenage population as well as the adult population. While many of the sources of stress for teenagers are different from the sources for adults, the effects are just as serious. Most teenagers have to deal with the internal and external pressure to achieve academically, to prepare for post-secondary education, to perform well in sports, and sometimes to use drugs and alcohol. Since it is impossible to avoid or prevent stress, it is essential to learn how to manage stress. Stress management is a combination of many factors, including removing the stressors; setting realistic goals and planning to achieve them; following a healthy lifestyle that includes proper nutrition and adequate rest, physical activity, and relaxation; and discussing problems with trusted and qualified adults.

Reactions to Stress

You have probably felt brief and immediate stress (such as a close call that almost resulted in a car accident), as well as longer-term stress (such as injuries that resulted from a car accident). Our bodies respond to short- and long-term stress differently (**Figure 3**).

The response to a brief stressor is activated by the sympathetic division of the autonomic nervous system. When the adrenal medulla (the centre of the adrenal gland)

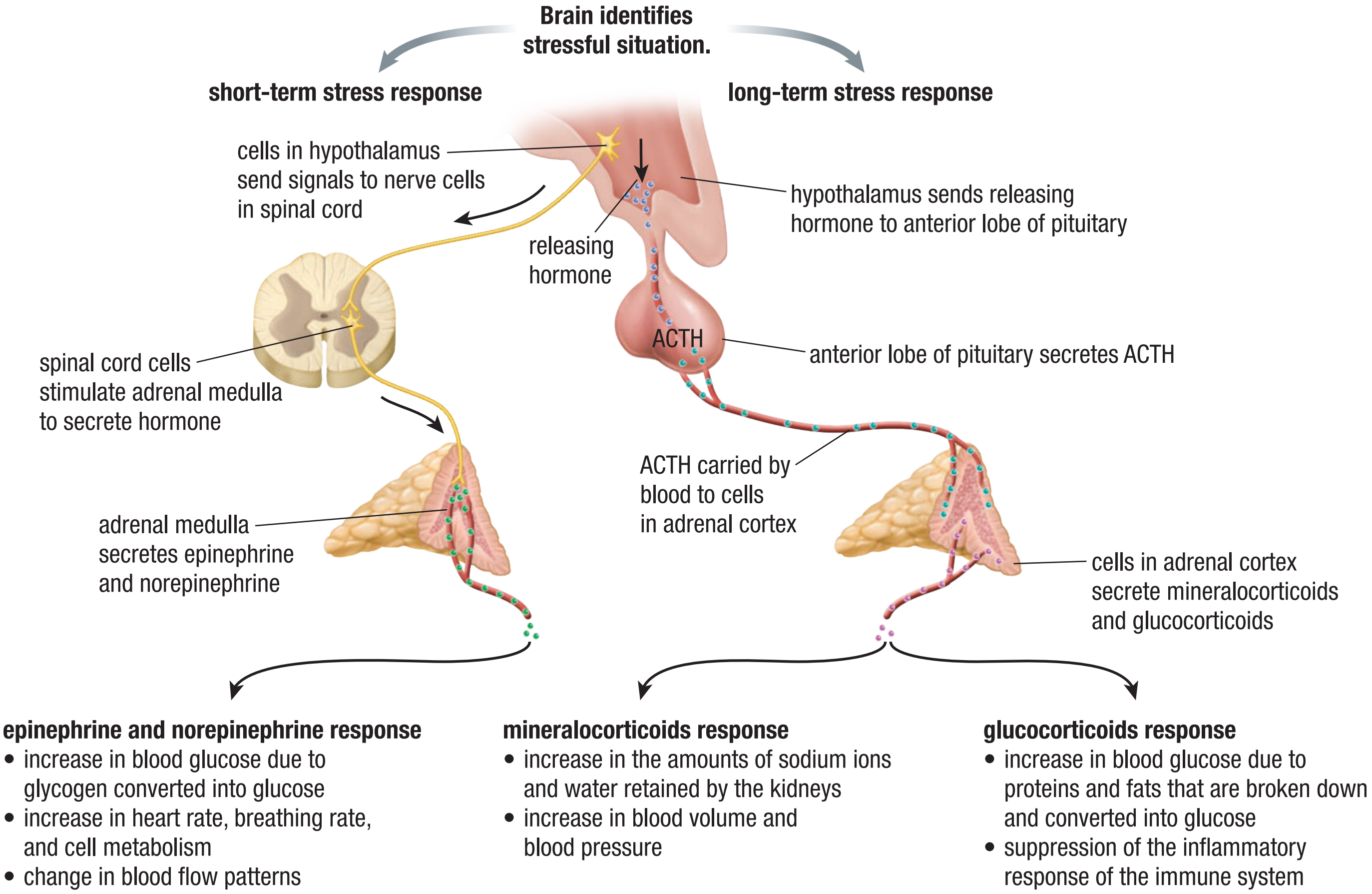

Brain identifies stressful situation.
short-term stress response
long-term stress response
cells in hypothalamus send signals to nerve cells in spinal cord
hypothalamus sends releasing hormone to anterior lobe of pituitary
releasing hormone
ACTH
anterior lobe of pituitary secretes ACTH
spinal cord cells stimulate adrenal medulla to secrete hormone
ACTH carried by blood to cells in adrenal cortex
adrenal medulla secretes epinephrine and norepinephrine
cells in adrenal cortex secrete mineralocorticoids and glucocorticoids
epinephrine and norepinephrine response
• increase in blood glucose due to glycogen converted into glucose
• increase in heart rate, breathing rate, and cell metabolism
• change in blood flow patterns
mineralocorticoids response
• increase in the amounts of sodium ions and water retained by the kidneys
• increase in blood volume and blood pressure
glucocorticoids response
• increase in blood glucose due to proteins and fats that are broken down and converted into glucose
• suppression of the inflammatory response of the immune system

Figure 3 Hormones secreted by the adrenal cortex and adrenal medulla play an important role in the responses to both short-term and long-term stress.

is stimulated, epinephrine and norepinephrine are released, preparing the body for fight or flight. When the source of the stress has passed, the parasympathetic division returns conditions such as heart rate and breathing rate to normal.

The response to a long-term stressful situation is different (Figure 3). The body detects that it has been destabilized, and it attempts to maintain homeostasis through a set of negative feedback systems. Some of these systems help stabilize the body. For example, if an injury results in a loss of blood, the **renin-angiotensin-aldosterone pathway** works to maintain sufficient blood pressure. If blood flow to the kidneys is reduced through blood loss, the kidneys secrete the hormone renin. Renin stimulates the production of angiotensin, which stimulates the secretion of the hormone aldosterone from the adrenal cortex. Aldosterone causes the reabsorption of sodium and water by nephrons in the kidneys. This water retention increases the body's fluid volume, which increases blood pressure.

renin-angiotensin-aldosterone pathway a negative feedback mechanism that attempts to maintain blood pressure

To mobilize a rise in blood glucose, which is needed to confront stress, the hypothalamus signals the pituitary gland to release adrenocorticotropic hormone (ACTH). ACTH then signals the adrenal cortex to release a glucocorticoid called cortisol. Glucocorticoids reduce inflammation, and cortisol helps maintain the blood glucose level. At the same time, the pancreas reduces insulin production, keeping the glucose level high. A spike in blood glucose is helpful when confronting a temporary stressor. If the elevation of the blood glucose level is ongoing, however, the set point, or the level at which the body keeps glucose, will rise. Chronically high levels of glucose can cause the cells to become insulin resistant. This means that the insulin released by the body can no longer be used effectively. Cells are unable to take in and use blood glucose, and it remains in the bloodstream. Eventually, it is excreted in urine, but the muscles never receive the energy they need.

Prostaglandins are secreted as part of the stress response, and at least one prostaglandin is involved in a feedback loop with ACTH during the stress response. Prostaglandins are locally acting molecules that are derived from fatty acids and produced in most nucleated cells. There are several different prostaglandins, with a variety of effects. Some prostaglandins dilate blood vessels, thereby increasing blood flow. Others make the neurons in the spinal cord sensitive to pain and initiate an inflammatory response and fever in response to tissue damage. When we take acetylsalicylic acid (ASA) or other analgesics (pain relievers), we are disrupting the production of prostaglandins and thus reducing the perception of pain. ASA is also known to prevent the production of the prostaglandins that promote the clotting of blood when a blood vessel is damaged. A small daily dose of ASA can reduce the risk of a heart attack or stroke caused by the formation of blood clots in people suffering from atherosclerosis. Reducing the clotting ability of the blood, however, entails the risk of prolonged bleeding if an injury occurs.

Shock

Trauma, allergic reactions, and severe illnesses can trigger extreme stress responses in the body. A traumatic event or injury can produce a condition called shock (not to be confused with an electric shock). The symptoms of shock include disorientation, pale skin, rapid heart rate, and low blood pressure. Shock can be life-threatening because body organs are not receiving enough blood.

Some severe allergic reactions can cause enormous stress. In an allergic reaction, the immune system overreacts to a foreign substance. In most allergic reactions, it is not the substance itself that causes harm, but the body's extreme reaction to the substance. The body overproduces histamine, which results in the rapid swelling of tissue throughout the body. The swelling of tissue in the airways makes some allergic reactions deadly. In extreme cases, air flow is blocked and blood flow is constricted. Severe allergies to insect venom and certain foods can cause anaphylaxis (or anaphylactic shock), which is life-threatening. A person in anaphylactic shock has the symptoms of shock listed above and, in addition, may have itching and hives, difficulty breathing and swallowing, swollen lips, and a swollen tongue. As you have learned, epinephrine dilates the airways and blood vessels. In an emergency, if an allergic reaction causes anaphylaxis, using a preloaded, auto-injecting syringe to inject epinephrine can save a person's life by restoring air and blood flow.

11.6 Review

Summary

- Stress is the body's response to stimuli, or stressors, that cause a disruption in homeostasis. The response is an attempt to restore homeostasis.
- Stress can be caused by a range of factors, from waiting for exam results to meeting someone new to starting a new school. Physical stress, such as exercising, can also cause a stress response. Different individuals may respond differently to the same stress.
- Symptoms of stress can include accelerated heart rate, sweaty hands, an upset stomach, and rapid breathing.
- Long-term exposure to stress has been associated with many diseases and negative health effects.
- The endocrine, nervous, and excretory systems are all involved in the stress response. The endocrine system secretes hormones, such as epinephrine and cortisol. The nervous system responds to brief stressors and also stimulates the endocrine system. The excretory system regulates the volume of fluid in the body and maintains or increases blood pressure during an emergency.

Questions

1. What was Hans Selye's contribution to our understanding of homeostasis? Summarize the three stages of the stress response. K/U T/I
2. How does the body return to homeostasis after a stress-inducing event? K/U
3. How does your body react to the stress caused by a teacher suddenly announcing a pop quiz? Sketch a feedback loop to illustrate your answer. T/I C
4. What are some examples of stressors that can cause extreme stress? K/U
5. What are the roles of the adrenal cortex and the adrenal medulla in the stress response? T/I C
6. What are four possible ways that anyone can manage or reduce stress? K/U
7. Stress is commonly regarded as a condition that can lead to death. Stress-like phenomena are common in other organisms. If stress is pathological, why has evolution not eliminated it? What are the advantages of stress? K/U T/I
8. Suppose a friend came to you and told you that he was feeling really stressed. K/U A
   (a) What is the definition of stress?
   (b) What is the physiology of the stress response you might see exhibited by your friend?
   (c) What are some of the ways that people use to deal with stress that are actually counterproductive? Explain.
   (d) What suggestions would you make to help your friend deal with his stress?
9. The Yerkes–Dodson law is an empirical relationship between arousal and performance represented on a continuum (**Figure 4**). Using the Internet and other sources, find out more about this law and how it is related to stress and brain function. 🌐 T/I

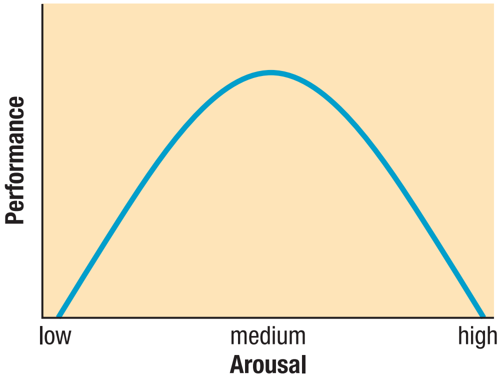


Figure 4

10. Stress is facilitated by two primary hormones: cortisol and adrenaline. These stress activators and modulators play significant roles in preparing the mind and, most specifically, the body for response to an overwhelming situation, but that response is intended to be short term. Prolonged stress begins to impact vital body organs and systems in a negative way. In fact, cortisol has been linked to a variety of health problems. Using the Internet and other sources, research how cortisol affects our health. 🌐 T/I

🌐 WEB LINK

CHAPTER 11 Investigations

Investigation 11.1.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Testing Learned Responses

The planarian is a type of freshwater flatworm (**Figure 1**). It has a simple nervous system that consists of sensory cells (its "brain") in the head region and groups of longitudinal nerve cords connected to transverse nerves in a ladder-like manner.

Figure 1

Although its nervous system is simple, a planarian can sense and respond to its environment to find an appropriate habitat, obtain food, and avoid predators and other dangers. For example, a planarian normally avoids bright light and orients itself toward darker areas that, in its natural habitat, provide protection from predators. However, a planarian can sometimes be "taught" or conditioned to avoid its preferred habitat using an appropriate negative stimulus, such as a puff of air or a bright light.

In this investigation, you will attempt to "teach" several planarians to avoid their preferred habitat, and you will observe whether all individuals learn at the same rate.

Testable Question

Can planarians learn to avoid their preferred habitat and, if so, do individual planarians "learn" at different rates?

Hypothesis/Prediction

Before you begin the experiment, make a prediction about what you think might happen. Write a testable hypothesis, noting the criteria you will consider.

Variables

With your partner, discuss the type of negative stimulus you will use to change the behaviour of the planarians. What are the dependent and independent variables in your experiment? Which variables can you control? Which variables are beyond your control?

Experimental Design

The subjects (three different planarians) will be stimulated with a harmless negative stimulus to determine the time required for each planarian to learn to avoid its preferred habitat (shaded area).

Equipment and Materials

- 3 planarians
- Petri dish or shallow transparent container
- enough water to cover the planarians
- stopwatch
- other equipment as required
- paper

Procedure

SKILLS HANDBOOK A1.2, A2.2

Discuss with your partner the procedure you will use to test each planarian's ability to learn and its speed of learning compared with other planarians. Have your teacher approve your procedure before you proceed.

Analyze and Evaluate

SKILLS HANDBOOK A5.4

(a) What variables did you measure and/or manipulate in this experiment? What type of relationship did you test? T/I

(b) Describe your experimental results, and compare your results with your classmates' results. Plot all the data for your class on an appropriate grid. T/I C

(c) Did your observations confirm your prediction? Did the experimental results support your hypothesis? Explain. T/I A

(d) Do you think the duration or strength of the stimulus affected your results? Explain. T/I A

(e) Do you think the frequency of the stimulation affected your results? Explain. T/I A

(f) Evaluate your experimental design. What could you do to improve the validity of your data? T/I A

Apply and Extend

(g) Answer the testable question: Do individual planarians “learn” at different rates? T/I

(h) How would you design an extension to the experiment to test whether the behaviour that your planarians learned is temporary or retained over the long term? T/I A

(i) Design an experiment to determine whether the planarians’ learning is dependent on chemical mechanisms. A

(j) Do you think you could retrain the planarians to prefer the shaded habitat? Discuss this question with your partner, and outline an experimental procedure you could use to answer it. C A

Investigation 11.2.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Investigating the Nervous System of an Invertebrate

The planarian may appear to be a simple organism. However, its nervous system is complex enough to enable it to cope effectively in its environment. In this investigation, you will design and carry out an investigation to help you learn how this organism senses and responds to its environment.

Testable Question

With your partner, choose one of the following questions, a variation of one of these questions, or an appropriate question of your own to investigate.

- Do planarians find their food using visual cues or another sense?
- What is the preferred habitat temperature of planarians?
- Do planarians respond to gravity?
- Do planarians have memory?
- Can planarians sense a magnetic field?
- Do planarians prefer still or moving water?
- How do planarians react to chemical stimuli (for example, a sugar solution)?
- How do planarians respond to touch?
- Do planarians respond to sounds? If so, which frequencies?

Hypothesis/Prediction

Before you begin the experiment, make a prediction about what you think will happen. Write a testable hypothesis, noting the criteria you will consider.

Variables

What are the dependent and independent variables in your experiment? What variables can you control? What variables are beyond your control?

Experimental Design

Write a brief description of an experimental design that you think will enable you to answer your testable question. *Your design should not include any stimuli or procedures that will cause undue harm to the planarians.*

Equipment and Materials

Identify any equipment and materials you will need.

Procedure

SKILLS HANDBOOK A1.2, A2.2

With your partner, write a detailed procedure, based on your experimental design. Have your teacher approve your experimental design and procedure before you proceed.

Analyze and Evaluate

SKILLS HANDBOOK A2.6

(a) What variables did you measure and/or manipulate in this experiment? What type of relationship did you test? T/I

(b) Did your observations confirm your prediction? Did your experimental results support your hypothesis? Explain. T/I

(c) Prepare a lab report that describes your investigation in detail. Be sure to include the following information in your report:

- your testable question
- your experimental design
- a list of the equipment and materials you used
- a description of the independent, dependent, and controlled variables
- a detailed description of your procedure
- your observations
- your conclusions
- your evaluation of your experimental design and procedure T/I C

Apply and Extend

(d) What do the results of your investigation tell you about the abilities of the nervous system of planarians? T/I A

(e) Suggest a different method you could use to investigate your testable question. Explain the advantage of using a different method to test the same question. T/I A

Investigation 11.5.1 OBSERVATIONAL STUDY

Exploring the Senses

Sensory perception relies on information that is sent to our brain from sensory receptors in our eyes, ears, nose, mouth, and skin. Touch receptors are the most widespread sensory receptors. We can feel touch all over our body, but our hands provide the most information about touch. Our other senses—smell, taste, hearing, and sight—have different kinds of receptors that relay different kinds of sensory information.

Purpose

In this observational study, you will observe different senses to better understand how the sensory receptors of the nervous system work to help you perceive your surroundings.

Equipment and Materials

Part A

- mathematical compass with a pencil, or a divider
- metre stick
- 2 toothpicks
- tape

Do not use the compass or divider without attaching the toothpicks. The compass and divider have sharp ends, which could easily puncture the skin.

Part B

- ruler

Part C

- pencil

Part D

- any necessary equipment for your self-directed activity

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Procedure

Part A: Two-Point Discrimination

1. Work with a partner. One of you will be the subject, and the other will be the observer.
2. Break the sharp tips off two toothpicks, and discard the tips. Tape one of the toothpicks along the pointed arm of the compass or one arm of the divider. The blunt end of the toothpick should protrude approximately 10 mm beyond the sharp steel point of the compass or the arm of the divider.
3. Tape the other toothpick along the length of the pencil in the compass or the other arm of the divider. The blunt end of the toothpick should protrude about 10 mm beyond the tip of the pencil or the arm of the divider.
4. You will test the palm of the hand, the back of the hand, the inside of the forearm, and the elbow or knee. The distances between the two points of the toothpicks will be 5 mm, 10 mm, 15 mm, or 20 mm. Using this information, prepare a table to record your observations.
5. If you are the observer, set the distance between the toothpicks at either 5 mm, 10 mm, 15 mm, or 20 mm. Do not reveal the distance to the subject (your partner).
6. Have the subject close his or her eyes. Gently touch one or both toothpick tips to the subject's skin. When touching both tips, ensure that both touch the skin at the same time. Repeat two or three times, randomly switching between touching one or both tips each time.
7. Ask the subject whether he or she feels one point of contact or two. Record the subject's answer. Repeat for each of the test locations on the body.
8. Repeat Steps 5 to 7 for each distance and each test location.
9. Switch the observer/subject roles, and repeat Steps 5 to 8.

Part B: The Blind Spot

10. Hold this book about 50 cm from your left eye, and fix your gaze on the black × in **Figure 1**.

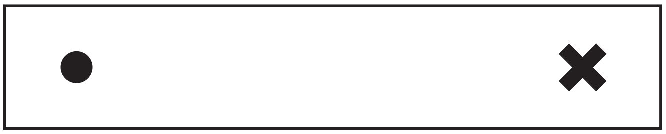


Figure 1

11. Close your right eye. Begin moving the book slowly toward your left eye while gazing steadily at the ×. Do not look away.
12. At some point, the black dot will seem to disappear. Stop moving the book when the dot disappears.
13. Have your partner measure the distance from the book to your left eye. Record the distance.
14. Repeat Steps 10 to 13 using your right eye and staring at the black dot this time. The black × will disappear at some point.

Part C: Eye Dominance

15. Hold a pencil in one hand. Face the corner of the room. Fix your gaze on the corner, where the walls meet. Extend your arm, and bring the top of the pencil into the middle of your field of view. Line up the pencil with the vertical line where the walls meet.
16. Close your right eye, and note the location of the pencil. Describe what happened to the location of the pencil when you closed your eye.
17. Close your left eye, and describe what happened to the location of the pencil.
18. Record your results. Compare your results with your classmates' results.

Part D: Self-Directed Activity

19. With a partner, choose one of the following sensory phenomena to observe and/or measure:
    - kinesthesia (awareness of position and movement of the body)
    - synesthesia (linking of two or more sensory pathways)
    - geometrical and colour perceptual illusions
    - colour blindness
    - determination of direction through hearing
    - tactile detection threshold
    - the ability to read Braille

    Alternatively, with your teacher's approval, you may choose another phenomenon that interests you.
20. Conduct research to learn the anatomy and physiology of the sensory phenomenon you chose.
21. Design an activity to demonstrate something unique about the phenomenon.
22. Write a report and prepare a presentation in the format of your choice to explain the phenomenon.

Analyze and Evaluate

Part A

(a) Based on your observations, what can you conclude about the distribution of touch receptors? Explain. T/I

(b) What do you think might be the advantage or disadvantage of this distribution of touch receptors? T/I

Part B

(c) Explain why the black dot disappeared. Draw a simple sketch to illustrate your explanation. T/I C

Part C

(d) How did your perception of the position of the pencil relate to the actual position of the pencil? How could you use this information to determine your dominant eye? T/I A

(e) What do we mean when we say that one eye is dominant over the other eye? T/I A

Apply and Extend

(f) What makes a blind spot in the visual field? Why are we not conscious of the blind spot even with only one eye open? A

(g) Which of the five senses do you think is the most important? Which sense would you be the most willing to lose? Explain your answers. T/I A

(h) Many animals that are prey for carnivores have eyes on the sides of their head, while most predators have stereo vision. How might each type of vision be an advantage for the predator or prey? A

(i) What have you learned in this investigation about the relationship between perception and reality? T/I A

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CHAPTER 11 SUMMARY

Summary Questions

1. Create a study guide based on the Key Concepts in the margin on page 514. For each point, write three or four sub-points that provide further information, relevant examples, and explanatory diagrams.
2. Look back at the Starting Points questions on page 514. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. Note how your answers have changed.

Vocabulary

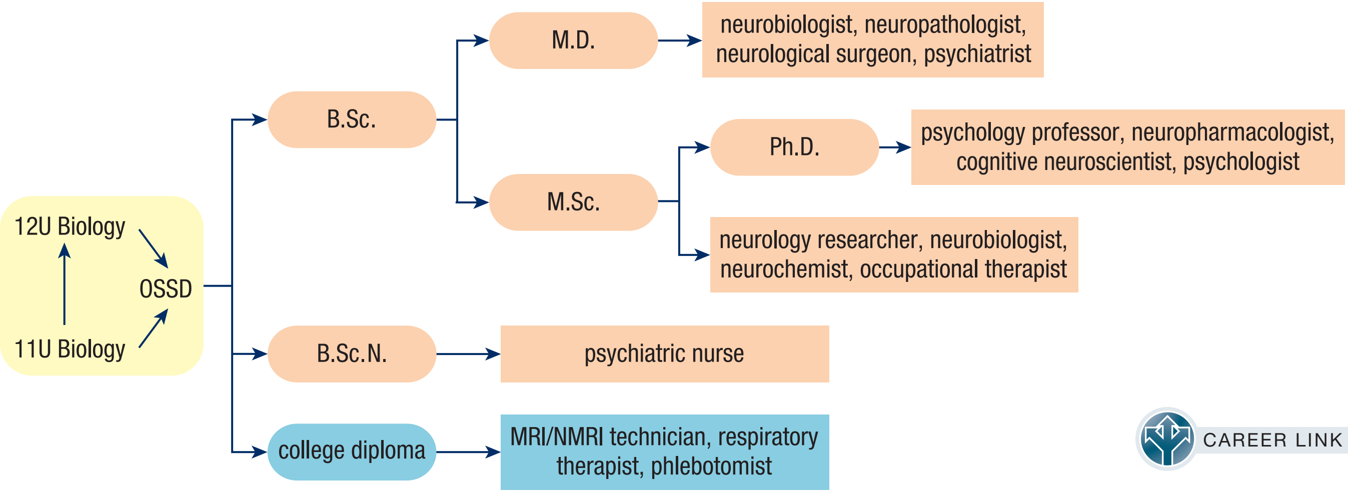
neuron (p. 516)
neural signalling (p. 516)
afferent neuron (p. 516)
interneuron (p. 516)
efferent neuron (p. 516)
dendrite (p. 517)
axon (p. 517)
glial cell (p. 518)
myelin sheath (p. 518)
node of Ranvier (p. 518)
central nervous system (CNS) (p. 518)
peripheral nervous system (PNS) (p. 518)
afferent system (p. 519)
efferent system (p. 519)
somatic system (p. 519)
autonomic system (p. 519)
sympathetic division (p. 519)
parasympathetic division (p. 519)
neural circuit (p. 520)
reflex arc (p. 520)
synapse (p. 522)
chemical synapse (p. 522)
neurotransmitter (p. 522)
synaptic cleft (p. 522)
electrical synapse (p. 523)
membrane potential (p. 523)
ion channel (p. 523)
resting potential (p. 523)
action potential (p. 524)
threshold potential (p. 524)
refractory period (p. 525)
meninges (p. 530)
cerebrospinal fluid (p. 530)
grey matter (p. 531)
white matter (p. 531)
medulla oblongata (p. 531)
cerebellum (p. 531)
pons (p. 531)
cerebrum (p. 532)
cerebral cortex (p. 532)
thalamus (p. 534)
blood–brain barrier (p. 534)
spinal nerves (p. 537)
cranial nerves (p. 538)
substantia gelatinosa (SG) (p. 539)
sensory adaptation (p. 543)
renin-angiotensin-aldosterone pathway (p. 552)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized undergraduate or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to the nervous system that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.



12U Biology
11U Biology
OSSD
B.Sc.
M.D.
neurobiologist, neuropathologist, neurological surgeon, psychiatrist
M.Sc.
Ph.D.
psychology professor, neuropharmacologist, cognitive neuroscientist, psychologist
neurology researcher, neurobiologist, neurochemist, occupational therapist
B.Sc.N.
psychiatric nurse
college diploma
MRI/NMRI technician, respiratory therapist, phlebotomist

CAREER LINK

CHAPTER 11 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which type of neuron transmits electric impulses to muscle fibres? (11.1) K/U
   (a) sensory
   (b) motor
   (c) association
   (d) secretory
2. What is the correct order for the transmission of an impulse in a motor neuron? (11.1) K/U
   (a) axon, dendrite, axon
   (b) Schwann cell, cell body, dendrite
   (c) axon, cell body, dendrite
   (d) dendrite, cell body, axon
3. Where in the neuron are neurotransmitters released? (11.2) K/U
   (a) in the mitochondria of the cell body
   (b) at the terminal knobs of dendrites
   (c) at the synaptic knobs of axon terminals
   (d) in Golgi bodies of the cell body
4. Which ions cause a neuron to repolarize after a nerve impulse passes? (11.2) K/U
   (a) carbon ions
   (b) hydrogen ions
   (c) potassium ions
   (d) oxygen ions
5. The brain and spinal cord are components of which system? (11.3) K/U
   (a) peripheral nervous system
   (b) central nervous system
   (c) sensory nervous system
   (d) autonomic nervous system
6. What is the peripheral nervous system composed of? (11.4) K/U
   (a) brain and cranial nerves
   (b) sensory receptors and nerves
   (c) brain and spinal cord
   (d) spinal nerves and sensory receptors
7. What are the two subsystems of the peripheral nervous system? (11.4) K/U
   (a) cervical and spinal
   (b) efferent and afferent
   (c) dorsal and ventral
   (d) vision and hearing
8. Which receptors detect changes in body position or acceleration? (11.5) K/U
   (a) mechanoreceptors
   (b) photoreceptors
   (c) thermoreceptors
   (d) nociceptors
9. Which human sense(s) can be considered the most complex? (11.5) K/U
   (a) hearing
   (b) touch
   (c) taste and smell
   (d) vision

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

10. The most complex neural circuit is the reflex arc. (11.1) K/U
11. Glial cells provide structural and functional support to neurons. (11.1) K/U
12. An action potential is an unequal distribution of positive and negative charges on either side of a neuron's cell membrane when the neuron is not conducting an impulse. (11.2) K/U
13. The cerebellum receives, filters, and relays sensory and motor information. (11.3) K/U
14. Some functions, such as long-term memory and consciousness, are equally distributed between the two cerebral hemispheres. (11.3) K/U
15. The somatic system of the peripheral nervous system controls the skeletal muscles that produce voluntary body movements. (11.4) K/U
16. Naturally produced painkillers block or reduce the binding of pain neurotransmitters to the substantia gelatinosa, but synthetic painkillers do not. (11.4) K/U
17. Sensory adaptation occurs when a stimulus continues at a constant level. (11.5) K/U
18. Sensory processing disorder occurs when stimuli are received abnormally but perceived normally. (11.5) K/U
19. Stress is the body's response to stimuli that cause a disruption in homeostasis. (11.6) K/U
20. The symptoms of shock include a slow heart rate and high blood pressure. (11.6) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

CHAPTER 11 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Small button-like swellings at the tip of an axon allow signals to be transmitted from one neuron to another. What are these swellings called? (11.1) K/U
   (a) cell bodies
   (b) axon hillocks
   (c) axon terminals
   (d) dendrites
2. Which part of a neuron receives sensory information? (11.1) K/U
   (a) dendrite
   (b) myelin sheath
   (c) node of Ranvier
   (d) axon
3. Which term refers to a neural circuit that travels through the spinal cord but does not require the coordination of the brain? (11.1) K/U
   (a) reflex circuit
   (b) reflex arc
   (c) afferent circuit
   (d) efferent circuit
4. What is a presynaptic cell? (11.2) K/U
   (a) neuron that carries the impulse to the synapse
   (b) neuron that carries the impulse away from the synapse
   (c) functional connection between neurons
   (d) neuron that connects to the effector
5. Which type of charge is carried by the inner surface of the plasma membrane in a resting neuron? (11.2) K/U
   (a) positive charge
   (b) negative charge
   (c) no charge
   (d) both positive and negative charge
6. Which term can be used to describe a membrane when the membrane potential is below the resting value? (11.2) K/U
   (a) depolarized
   (b) repolarized
   (c) hyperpolarized
   (d) hypopolarized
7. Which statement about the brain is correct? (11.3) K/U
   (a) The outer portion of the brain is covered with cell bodies.
   (b) The outer portion of the brain has no meninges.
   (c) The outer portion of the brain exists in an oxygen-free environment.
   (d) The outer portion of the brain is composed of grey matter.
8. What does the hindbrain of a vertebrate develop into? (11.3) K/U
   (a) medulla oblongata
   (b) cerebrum
   (c) pons
   (d) brain stem
9. What is one of the functions of the cerebellum? (11.3) K/U
   (a) to coordinate skeletal muscle activity
   (b) to produce pituitary hormones
   (c) to serve as a centre for speech
   (d) to serve as a centre for hearing
10. Which statement best describes sympathetic nerves? (11.4) K/U
    (a) They have short preganglionic and short postganglionic nerves.
    (b) They have long preganglionic and long postganglionic nerves.
    (c) They have short preganglionic and long postganglionic nerves.
    (d) They have long preganglionic and short postganglionic nerves.
11. Which part of the brain receives signals from the taste receptors? (11.5) K/U
    (a) hypothalamus
    (b) hippocampus
    (c) cerebellum
    (d) thalamus
12. Which of the following best describes stress? (11.6) K/U
    (a) physical only
    (b) physical, psychological, and emotional
    (c) psychological and emotional
    (d) emotional only

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

13. Neurons are cells that are specialized for the reception of electrical signals only. (11.1) K/U
14. Neurons have axons that receive information and conduct signals toward the cell body. (11.1) K/U

15. In an electrical synapse, neurotransmitter molecules are released by a presynaptic neuron, diffuse across a narrow synaptic cleft, and bind to receptors in the plasma membrane of a postsynaptic cell. (11.2) K/U
16. Octopamine is a neurotransmitter that is known to be involved in the feeding activity of insects. (11.2) K/U
17. Cerebrospinal fluid allows only selected substances to enter the blood–brain barrier. (11.3) K/U
18. The thalamus receives, filters, and relays sensory and motor information. (11.3) K/U
19. The autonomic system is mainly conscious and voluntary. (11.4) K/U
20. The 31 pairs of cranial nerves transmit motor, sensory, and autonomic signals between the spinal cord and the rest of the body. (11.4) K/U
21. In the auditory system, photoreceptors detect light at particular wavelengths and convert the stimuli to nerve impulses. (11.5) K/U
22. We usually think of the five senses but, in reality, there are nearly twice as many sensory abilities involved in homeostasis. (11.5) K/U
23. Everyone experiences stress in the same way. (11.6) K/U
24. Prostaglandins are secreted as part of the stress response, and at least one prostaglandin is involved in a feedback loop with ACTH during the stress response. (11.6) K/U

Match each term on the left with the most appropriate description on the right.

25.

(a) parasympathetic division	(i) subdivision of the efferent system, within the peripheral nervous system; regulates the internal environment
(b) autonomic system	(ii) coordinating centre for mechanical and chemical actions in the body; made up of the brain and spinal cord
(c) central nervous system (CNS)	(iii) part of the body that generally increases energy consumption and prepares the body for action
(d) peripheral nervous system (PNS)	(iv) all the parts of the nervous system, excluding the brain and spinal cord, that relay information between the CNS and other parts of the body
(e) sympathetic division	(v) part of the body that stimulates activities involved in acquiring and conserving energy (11.1) K/U

26.

(a) action potential	(i) voltage difference across a nerve cell membrane of an unstimulated neuron; usually negative
(b) membrane potential	(ii) potential at which an action potential is generated by a neuron
(c) resting potential	(iii) voltage difference across a nerve cell membrane when the nerve is excited
(d) threshold potential	(iv) period in which the threshold that is required for the generation of an action potential is much higher than normal
(e) refractory period	(v) electrical potential of a membrane, which results from an imbalance of charge on either side of the membrane (11.2) K/U

Write a short answer to each question.

27. List the components of a neural signalling pathway in the order they occur. (11.1) K/U
28. In your notebook, complete the following description of a reflex arc by filling in the missing words:
    Your finger touches a hot pot on a stove. Information is carried via the ________ neurons to the ________ in the spinal cord, which relay the information via the ________ neurons to the effector, which responds. (11.1) K/U
29. What allows the myelin sheath to act as an electrical insulator? (11.1) K/U
30. What are the nodes of Ranvier, and what is their function? (11.1) K/U
31. What structure is found only in electrical synapses, not in chemical synapses? (11.2) K/U
32. Why does a neuron plasma membrane need a refractory period? (11.2) K/U
33. (a) What is the threshold potential (in mV)?
    (b) When the threshold potential is reached, what happens to the Na^+ channels? (11.2) K/U
34. What are the effects of the degeneration of acetylcholine-releasing neurons in people who have Alzheimer's disease? (11.2) K/U
35. What is the difference between white matter and grey matter? (11.3) K/U
36. Name the four lobes of the cerebral cortex. (11.3) K/U
37. Explain the purpose of the blood–brain barrier. (11.3) K/U

38. Compare the function of the sympathetic division of the autonomic nervous system with the function of the parasympathetic division. (11.4) K/U

39. What is pain? (11.4) K/U

40. What are endorphins? (11.4) K/U

41. What is echolocation, and when is it useful? (11.5) K/U

42. What is the function of the Eustachian tube? (11.5) K/U

43. Name and explain the negative feedback pathway that attempts to maintain blood pressure if an injury results in a loss of blood. (11.6) K/U

44. How does epinephrine stop anaphylactic shock? (11.6) K/U

Understanding

45. Identify the three neurons that are involved in a reflex arc. List these neurons in the order they are used to complete the reflex arc. (11.1) K/U

46. Compare afferent neurons and efferent neurons. (11.1) K/U

47. What causes a membrane potential? (11.2) K/U

48. Use **Figure 1** to answer the following questions. (11.2) K/U

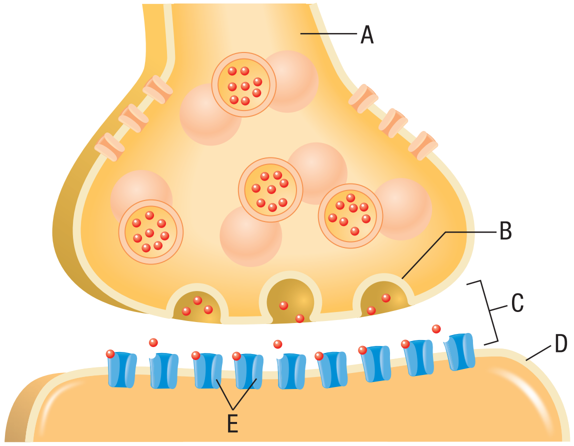


Figure 1

(a) Is this a chemical synapse or an electrical synapse? What structure (either present or absent) tells you which type of synapse it is?

(b) In this synapse, which structure represents the synaptic cleft?

(c) In this synapse, which structure represents the axon terminal of a presynaptic cell?

(d) What is happening in structure B?

(e) In structure D, neurotransmitter molecules diffuse across the cleft and bind to receptors in the plasma membrane of the postsynaptic cell. What happens next?

49. Distinguish between the central nervous system and the peripheral nervous system. (11.3, 11.4) K/U

50. How is the cerebrum anatomically divided? (11.3) K/U

51. Use **Figure 2** to answer the following questions. (11.5) K/U

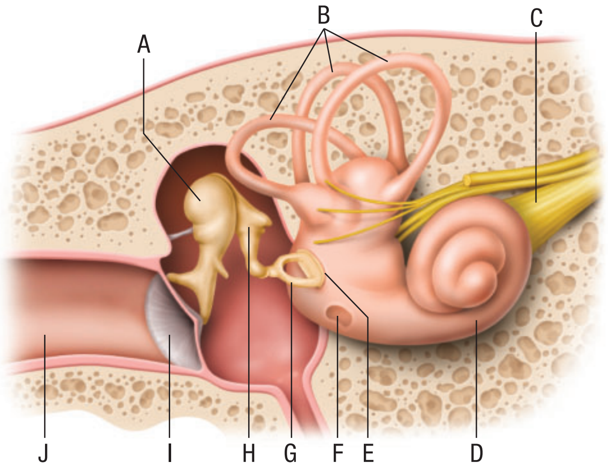


Figure 2

(a) Which letter identifies the tympanic membrane?

(b) Which letter identifies the structure that vibrates and directly creates the pressure waves in the fluid in the cochlea?

(c) Which letter identifies the structure that transmits auditory signals to the brain?

52. (a) What natural pain suppression system does the CNS have?

(b) How does this pain suppression system work? (11.5) K/U

Analysis and Application

53. During a physical examination, a doctor taps the side of a patient's knee with a small rubber hammer. (11.1) K/U T/I

(a) Explain what the doctor is testing.

(b) Describe the neural circuit that is involved.

54. Neurons can excite 200 to 1600 times per second, and an impulse can travel at up to 400 km/h. What physical characteristics would the axon of a neuron need for the action propagation to be the fastest possible? (11.1) K/U T/I

55. A toxin interferes with the opening of the Na^+ channels in the postsynaptic membrane, causing them to open more slowly when bound to a neurotransmitter. What would be the effect on formation of an action potential in the postsynaptic membrane? (11.2) K/U T/I

56. One effect of alcohol is to make the person consuming it feel slow and sluggish. It does this by affecting two important neurotransmitters. Which neurotransmitters are these likely to be, and how do they slow the body's reaction to stimuli? (11.2) K/U T/I

57. An action potential graph is shown in **Figure 3**. (11.2) K/U T/I A

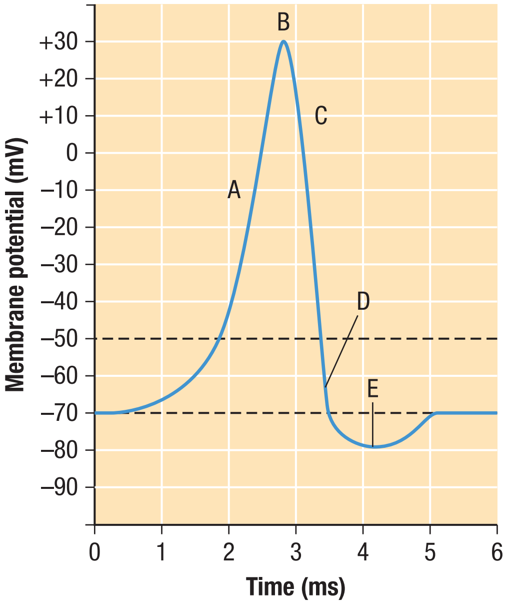


Figure 3

(a) At what point in this graph are Na^+ channels opening and K^+ channels closing?

(b) At what point in this graph are many Na^+ channels open and many K^+ channels closed?

58. Two stimuli are applied to a neuron in quick succession. The first stimulus measured 1 mV (millivolts), and the second stimulus measured 10 mV. The action potentials of the neuron were recorded. Which graph in **Figure 4** represents the correct pattern? Explain your reasoning. (11.2) K/U T/I A

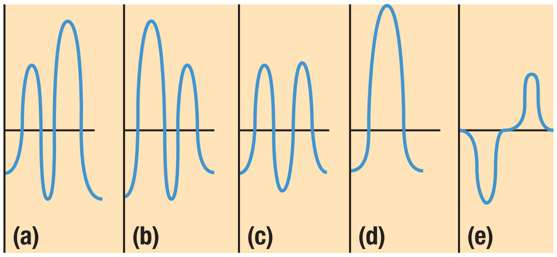


Figure 4

59. People with Parkinson's disease tremble involuntarily. Their muscles become rigid and stiff, and they lose the ability to make rapid, spontaneous movements. As well, their body is bent or flexed when they walk, and they may have difficulty maintaining their balance. Based on the symptoms described, which neurotransmitter is likely the cause of Parkinson's disease? Is there too much or not enough of this neurotransmitter? (11.2) K/U T/I

60. Compared with the human brain, which part of the brain is more developed in bats? Explain your choice. (11.3) K/U T/I

61. Many people think that a turkey dinner makes them sleepy because turkey contains a high level of tryptophan, which the body uses to make serotonin. Using this information, explain why a turkey dinner could make you sleepy. (11.2, 11.3) K/U T/I A

62. How would the destruction of the motor areas of the right cerebral cortex affect voluntary movement and sensation? What part of the body would be affected? (11.3) K/U T/I

63. Explain why the adaptation of pain receptors would not be desirable, but the adaptation of other sensory systems is beneficial. (11.5) K/U T/I

64. Explain how a flushed face after exertion is a homeostatic mechanism. (11.5) K/U T/I

Evaluation

65. A man has injured his back and arm in a fall. His doctor suspects that there is a blockage in a neural circuit. Read each symptom below. Then use **Figure 5** and your knowledge about neural circuits to determine if a blockage exists and, if so, where you think it is (A, B, C, any combination of these three locations, or no blockage). Explain your reasoning for each case. (11.1) T/I

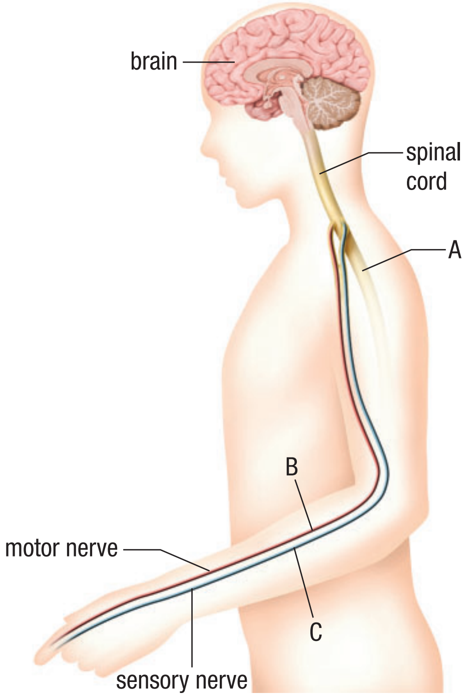


Figure 5

(a) The patient can move his hand, but cannot feel a pinprick on his finger.

(b) The patient can feel a pinprick on his finger, but cannot move his hand.

(c) The patient can move his hand and feel a pinprick on his finger.

66. What effect does a lack of salt have on the nervous system? (11.1, 11.2) K/U T/I

67. Cholinesterase is an enzyme that deactivates acetylcholine. Some nerve poisons block the function of cholinesterase. How might exposure to this type of nerve poison affect the person exposed? (11.2) K/U T/I

68. Drugs that stimulate the nervous system are called agonists, and drugs that inhibit the nervous system are called antagonists. Drugs can be designed to affect specific neurotransmitters or neuroreceptors and thereby target different parts of the nervous system. Non-narcotic analgesics, such as acetylsalicylic acid and ibuprofen, reduce pain by blocking the production of prostaglandin at the source of the pain. Acetaminophen reduces pain by inhibiting the production of brain prostaglandins. Explain why a dentist may suggest alternating acetaminophen and acetylsalicylic acid for an adult with a severe toothache. (11.2) K/U T/I A

69. You know that exercise is good for your body, but did you know that it is also good for your brain? (11.1, 11.2, 11.3) K/U T/I A
    (a) Based on what you have learned, create a list of brain exercises that you think would be effective for
        (i) reinforcing existing neural pathways
        (ii) creating new neural pathways
    (b) Which of these brain exercises do you think would be most difficult for a person to master? Explain your reasoning.

70. Create a poem, song, or rap for elementary or middle school students to explain how stress affects the nervous system and the homeostasis of the body in general. (11.6) K/U T/I C A

Reflect on Your Learning

71. Based on what you have learned in this section, why do you think that people respond to and handle stress differently? (11.6) K/U A

72. Many sports, such as hockey and football, require the participants to wear helmets. However, other sports, such as skiing and snowboarding, may not. T/I A
    (a) Based on what you have learned about the nervous system, do you think helmets should be mandatory for anyone who is playing a sport that involves a risk of a head or neck injury? Why or why not?
    (b) After studying this chapter, would you wear a helmet for sports in which a head injury is a possibility? Why or why not?

73. People who have suffered a spinal cord injury still need to get from place to place every day. What modifications or adjustments do you think they have to make? Put yourself in their "wheels" for a day. T/I C A
    (a) Make a list of your daily travels, including all the rooms, buildings, and places you generally go.
    (b) Beside each location, state whether you could gain access to it yourself or whether you would need assistance.
    (c) Are there any locations that you could not access by yourself?
    (d) Consider why these locations are important to you, and what you would have to do to gain access.
    (e) Suggest ways that these locations could be made more accessible.
    (f) Estimate how much longer your daily routine might take if you were unable to walk.
    (g) Do you think people would treat you differently than they do now if you were unable to walk? How would you respond to them if they did? Explain your thinking.
    (h) What other medical issues might you have to contend with if you suffered a spinal cord injury?

74. Some people believe that the National Hockey League (NHL) should ban blows to the head and should follow the lead of other organizations, such as Hockey Canada, by creating a zero-tolerance approach to head shots. Neurosurgeons and concussion specialists are strongly in favour of these ideas. T/I C A
    (a) Do you think head shots should be banned from hockey at all levels? Explain your reasoning.
    (b) Do you know anyone, or have you heard of anyone, who has had to leave a sport due to multiple concussions? How do they feel about this? How do you feel about it?
    (c) Based on what you know about the danger of multiple concussions, do you think all sports organizations should take a firmer stand on bad hits? What should their position be?
    (d) If a sports organization does not take any action and a participant is badly injured or disabled, should the participant have the right to sue the organization and/or the perpetrator or lay criminal charges?

Research

WEB LINK

75. In March 2009, actress Natasha Richardson fell and hit her head while skiing in Québec. She was conscious after the incident and declined the ski patrol's offer of a trip to the hospital for a medical examination. Within a few hours, she was rushed to the hospital in critical condition. She died from an epidural hematoma, or what is also known as "talk and die" syndrome. Using the Internet and other sources, create a public awareness poster to help others better understand this serious condition. Include answers to the following questions on your poster:
    - What is an epidural hematoma? What causes it?
    - Why is an epidural hematoma also called "talk and die" syndrome?
    - What are the signs and symptoms of this syndrome?
    - How is an epidural hematoma treated, and how urgent is this treatment? What should be done when a possible brain injury occurs?
    - How can this type of brain injury be prevented? T/I A

76. Cells produce many proteins and enzymes that are used for regulation, growth, and structural elements. Cells also produce their own messenger molecules or neurotransmitters, which may influence the functioning of adjacent neurons. Psychoactive drugs (drugs that can produce mood changes and distorted perceptions) affect neurotransmitters by interrupting how the neurotransmitters affect cells. These drugs either block or overproduce an impulse. Tetrahydrocannabinol (THC) is a psychoactive drug used to achieve medical benefits by blocking the effects of neurotransmitters. Using the Internet and other sources, prepare a brief report that answers the following questions about the medical benefits of THC:
    - Which neurotransmitter does THC block?
    - How does THC enhance the appetite of patients who are undergoing chemotherapy? Explain, in detail, the neurological responses that increase the appetite.
    - THC has also been used to reduce eye pressure in glaucoma patients, with varying results. How does THC work neurologically in this situation? What seems to be the end result of the few studies that have been done to date?
    - Every drug has side effects. What side effects can THC produce in patients who use it? T/I C A

77. In the past, many spinal cord injuries resulted in a permanent loss of body functions. Recent advancements in spinal cord research suggest that this may soon change. Using the Internet and other sources, research what scientists have learned about possible nerve regeneration. Present your findings to your classmates in a report that includes answers to the following questions:
    - What is a spinal cord injury? Where can it occur?
    - What is the difference between paraplegia and quadriplegia?
    - What is the difference between a complete spinal cord injury and an incomplete spinal cord injury?
    - What are the five types of incomplete spinal cord injuries?
    - What are the body's primary and secondary responses to spinal cord injuries?
    - What is the initial treatment for a spinal cord injury?
    - What are the two recent discoveries that may make it possible for neurons to regenerate and reconnect with their target cells? T/I C A

78. Mirror neurons, which were discovered in the early 1990s, could help to explain how we learn through mimicry and why we empathize with others. Mirror neurons are brain cells that have the same response when we perform an action and when we witness someone else perform this action. Using the Internet and other sources, research what we know about mirror neurons. Prepare a report that includes the following information:
    - where and how mirror neurons were discovered
    - what the circumstances of their discovery were
    - what the first human mirror neuron study was investigating
    - how scientists think mirror neurons help us feel empathy for others
    - where mirror neurons are found in the brain T/I C A

79. In the past, medical practitioners and first-aid providers believed that a person with a head injury must be wakened once an hour for 24 h. If the person was not wakened, the possibility of dying while asleep was greatly increased. We now know that this is not true. T/I C A
    (a) What changes in medicine do you think have changed this standard assessment tool?
    (b) If a person suffers a head or neck injury, what is the first thing that should be done?
    (c) What is the one thing that should not be done, if it can be avoided? Explain why.
    (d) In what circumstances might this one thing have to be done?

Upsetting the Balance

The stability of the internal environment of the human body is remarkable, given the diverse range of environmental conditions that it is exposed to. Homeostasis is a dynamic interplay between outside factors that tend to shift the internal environment and internal control mechanisms that oppose such shifts. The cells, organs, and body systems require a fairly narrow range of conditions to function optimally. Some factors, however, are severe enough to upset homeostasis, with potentially serious repercussions for short-term health and long-term survival.

Recall that homeostasis includes both negative and positive feedback mechanisms, which have three functional components: sensor, integrator, and effector. Disease, genetic disorders, infection, diet, lifestyle, drug use, environmental toxins, and extreme environmental conditions (such as extreme cold, extreme heat, extremes in pressure, and low oxygen) are examples of factors or stressors that can upset the body's homeostasis (**Figure 1**). Many of these factors are within our control as individuals. For example, we can eat a healthy diet; drink sufficient water; maintain an active lifestyle; avoid unnecessary drug use; avoid exposure to harmful products that contain toxic components; and avoid exposure to extreme heat, cold, pressure, and low oxygen. However, some factors are not within our direct control, such as our genetic composition, exposure to disease or infection, and accidental exposure to extreme conditions, drugs, or toxins.

Figure 1

Issue

There are many different factors that can shift the human body away from homeostasis, compromising both short-term health and long-term survival. What are some of these critical, homeostasis-upsetting factors, and how can these factors be addressed?

Goal

To prepare a sample case study that illustrates how a chosen factor can upset the body's homeostasis, and to propose a plan of action that will correct or prevent the problem

Procedure

1. Select and define one factor from the following list:
    - a disease
    - a genetic disorder
    - an infection (for example, bacterial, viral, or protozoan)
    - diet
    - lifestyle
    - drug use
    - an environmental toxin
    - extremes in physical environmental conditions, such as extreme cold and heat, high and low pressure, high and low oxygen levels, or dehydration and hyperhydration

    Alternatively, with your teacher's approval, you may choose a different factor that interests you.
2. Research the factor you chose, including its impact on homeostasis and the body. Consider both short-term and long-term effects on health, and identify knowledge gaps in the research. The following questions may help to guide your research:
    - What is the physiological relationship between homeostasis and the factor you chose?
    - What body systems are affected by and respond to this factor?
    - What symptoms are likely to be exhibited as a result of this factor?
    - What control mechanisms does the body normally use to oppose the changes caused by this factor?
    - What type of feedback mechanism is involved in the homeostatic response?
    - What are the implications of this factor (if any) on organ systems other than the systems that are directly affected?
    - What additional research will assist in better understanding the impact of this factor on homeostasis and human health, and in mitigating its harmful impacts? WEB LINK

3. Using real or created data, based on your research, create a case study as an example. In your case study, include a profile of the individual who is affected by your chosen factor. Personal data about this individual could include age, sex, height, and weight. Social data could include family structure and composition, occupation, lifestyle, physical activities, and hobbies. Medical data could include blood pressure, red and white blood cell count, allergies, kidney function, endocrine function, toxicity screen, and other relevant parameters. Include tables and graphs, as needed, to explain your findings. Also include a description of how your chosen factor affects homeostasis.
4. Prepare a plan of action for the individual in your case study. Include recommended actions to avoid, correct, or ameliorate the condition described in your case study, as well as realistic goals that the individual can use as indicators of success.

Apply and Extend

(a) Answer the questions that are the most relevant to your chosen factor. K/U A
   (i) If the chosen factor is a disease or disorder, what is the cause of the disease or disorder? What are the possible treatments, and what is the prognosis?
   (ii) If the factor is a lifestyle choice, can homeostasis be regained? What corrective measures need to be taken? Will these measures include medical intervention?
   (iii) If the factor is an environmental factor, can the factor be avoided? What is the source of the factor? How can the risk associated with the factor be minimized or completely eliminated?

(b) What additional research will assist in better understanding the impact of this factor on homeostasis and human health, and in mitigating its harmful impacts? K/U A

Communicate

(c) Present a summary of your case study and your plan of action to the class in the form of a 5 min slide presentation or video documentary, and a one- or two-page written report. C

WEB LINK

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

✓ Demonstrate understanding of homeostasis and the importance of maintaining homeostasis within the body.

✓ Describe the specific feedback mechanisms and organ systems involved in responding physiologically to the homeostasis-challenging factor you chose.

✓ Explain the short-term and long-term effects of the factor on human health, including examples to illustrate your knowledge.

✓ Demonstrate understanding of the physiological mechanisms and systems that respond to the factor.

✓ Describe how these responses manifest themselves in recognizable symptoms.

Thinking/Investigation

✓ Analyze and evaluate the sources and the scientific information obtained from these sources.

✓ Provide a rationale for the goals and the recommended actions in your plan.

Communication

✓ Explain clearly and concisely how homeostatic mechanisms respond to the factor you chose.

✓ Explain the plan of action you would propose to treat or ameliorate the condition described in your case study.

✓ Communicate your plan of action in an audiovisual format using a variety of multimedia tools.

Application

✓ Apply your knowledge of homeostasis to make a list of behavioural decisions that can help the body maintain homeostasis (for example, a healthy lifestyle or measures to avoid infection).

UNIT 4 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which term refers to the maintenance of the body's internal environment at relatively constant levels? (9.1) K/U
   (a) feedback
   (b) homeostasis
   (c) physiology
   (d) natural selection
2. Which term refers to the process in which an environmental stimulus triggers a response that compensates for changes in the internal/external environment? (9.2) K/U
   (a) negative feedback
   (b) positive feedback
   (c) physiological feedback
   (d) anatomical feedback
3. Which term refers to organisms that obtain heat primarily from the external environment? (9.3) K/U
   (a) exotherms
   (b) endotherms
   (c) ectotherms
   (d) isotherms
4. What is the main form of the nitrogenous wastes released by mammals to their environment? (9.4) K/U
   (a) nitrate
   (b) amino acids
   (c) ammonia
   (d) urea
5. The excretory system of most annelids and adult mollusks consists of tubules. What are these tubules called? (9.5) K/U
   (a) metanaphridia
   (b) Malpighian tubules
   (c) nephrons
   (d) hepatic tubules
6. Urine leaves the urinary bladder through a tube. What is this tube called? (9.5) K/U
   (a) collecting duct
   (b) renal vein
   (c) renal pelvis
   (d) urethra
7. In which organism are metanaphridia found? (9.5) K/U
   (a) annelid
   (b) mammal
   (c) flatworm
   (d) insect
8. In mammals, where is the glomerulus located? (9.5) K/U
   (a) within the Bowman's capsule
   (b) within the descending segment of the loop of Henle
   (c) within the distal convoluted tubule
   (d) within the ascending segment of the loop of Henle
9. Which of the following is an important function of the endocrine system? (10.1) K/U
   (a) It provides mechanisms for rapid responses to changes in the body.
   (b) It allows for mechanisms that control gene action.
   (c) It inhibits nervous system action on muscles and glands.
   (d) It maintains a constant yet dynamic internal fluid environment.
10. Which of the following regulates the pituitary gland most directly? (10.2) K/U
    (a) thyroid gland
    (b) hypothalamus
    (c) adrenal gland
    (d) pineal gland
11. Which anterior pituitary hormone has a generalized effect and has receptors on almost every cell in the body? (10.2) K/U
    (a) ACTH
    (b) growth hormone
    (c) prolactin
    (d) ADH
12. What causes gigantism? (10.2) K/U
    (a) hypersecretion of gonadotropin during childhood
    (b) hypersecretion of growth hormone during childhood
    (c) hyposecretion of thyroxine during childhood
    (d) hypersecretion of growth hormone during adulthood
13. Which cells secrete glucagon? (10.3) K/U
    (a) alpha cells of the islets of Langerhans
    (b) beta cells of the islets of Langerhans
    (c) alpha cells of the pituitary gland
    (d) beta cells of the pituitary gland
14. Which hormone is a natural steroid hormone? (10.5) K/U
    (a) insulin
    (b) estrogen
    (c) epinephrine
    (d) oxytocin

15. Which hormone is responsible for stimulating contractions of the uterus? (10.7) K/U
    (a) insulin
    (b) UCH
    (c) glucagon
    (d) oxytocin
16. Which term refers to nervous system cells that send and receive electrical signals? (11.1) K/U
    (a) receptors
    (b) neurons
    (c) sensors
    (d) glial cells
17. What is the typical resting potential of a neuron? (11.2) K/U
    (a) –90 mV
    (b) –70 mV
    (c) –100 mV
    (d) –60 mV
18. In vertebrates, what does the CNS consist of? (11.3) K/U
    (a) brain and reflexes
    (b) spinal cord and grey matter
    (c) brain and spinal cord
    (d) brain and grey matter
19. Which neurons transmit sensory information to the CNS? (11.4) K/U
    (a) efferent neurons of the CNS
    (b) afferent neurons of the PNS
    (c) somatic neurons of the PNS
    (d) somatic neurons of the sympathetic division
20. What is the function of pain? (11.5) K/U
    (a) It causes an organism to move away from or otherwise decrease its exposure to a damaging stimulus.
    (b) It elicits a reflex response.
    (c) It protects an organism from encountering harmful conditions.
    (d) It works faster than conscious thought.
21. Which part of the nervous system controls the fight-or-flight response to stress? (11.6) K/U
    (a) parasympathetic
    (b) sympathetic
    (c) PNS
    (d) none of the above

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

22. Sweating when you are hot is an example of a homeostatic mechanism. (9.1) K/U
23. Blood oxygen regulation is an example of a positive feedback control of homeostasis. (9.2) K/U
24. Estivation is an extended period of torpor experienced by an animal during the winter, when the environment is too cold and food is scarce. (9.3) K/U
25. Osmoregulation is closely linked to the process of circulation. (9.4) K/U
26. Human kidneys have tubules called nephrons. (9.5) K/U
27. The products of the endocrine glands are hormones. (10.1) K/U
28. The hypothalamus and the pituitary gland control other endocrine cells and glands throughout the body. (10.2) K/U
29. Glucagon lowers blood glucose by stimulating glycogen, fat, and protein degradation. (10.3) K/U
30. The use of illegal steroids has led to a very negative perception of the word “steroid.” (10.5) K/U
31. Testosterone is the primary sex hormone in females, while estrogen is the primary sex hormone in males. (10.7) K/U
32. Afferent neurons conduct information from sensory receptors to interneurons. (11.1) K/U
33. Neurons make connections with one type of synapse. (11.2) K/U
34. The medulla oblongata connects the spinal cord to the cerebellum. (11.3) K/U
35. The autonomic nervous system is organized into the sympathetic and unsympathetic divisions. (11.4) K/U
36. Mechanoreceptors detect body position. (11.5) K/U

UNIT 4 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which two organ systems are the most important for the maintenance of homeostasis? (9.1) K/U
   (a) lymphatic and circulatory systems
   (b) digestive and circulatory systems
   (c) nervous and endocrine systems
   (d) endocrine and circulatory systems
2. Which component of a negative feedback mechanism is responsible for producing the effect that counteracts the original environmental change away from homeostasis? (9.2) K/U
   (a) stimulus
   (b) sensor
   (c) effector
   (d) integrator
3. Which term refers to organisms that obtain heat primarily from internal physiological sources? (9.3) K/U
   (a) allotherms
   (b) ectotherms
   (c) exotherms
   (d) endotherms
4. What is required when urea, rather than uric acid, is used as the main form of nitrogenous waste? (9.4) K/U
   (a) equal amounts of energy and water
   (b) less energy and more water
   (c) more energy and less water
   (d) less energy and water
5. Which term refers to the non-selective movement of water and several solutes into the tubules of the excretory system? (9.5) K/U
   (a) reabsorption
   (b) release
   (c) filtration
   (d) secretion
6. Which segment of the mammalian nephron receives the filtrate first? (9.5) K/U
   (a) ascending segment of the loop of Henle
   (b) distal convoluted tubule
   (c) descending segment of the loop of Henle
   (d) Bowman's capsule
7. Why do the target tissues for steroid hormones and thyroid hormones not have membrane receptors for these hormones? (10.1) K/U
   (a) The hormones are small enough to diffuse directly into the cell.
   (b) The hormones stimulate the cell by changes in electrical activity.
   (c) The hormones are soluble in the lipid bilayer.
   (d) The hormones enter the cells by ion channels.
8. If the production of melanocyte-stimulating hormone were increased, what would you expect to happen? (10.2) K/U
   (a) increase in reproductive cycles
   (b) decrease in milk production in females
   (c) changes in kidney function for retention of water
   (d) increase in pigmentation of the skin
9. Which gland regulates milk release, water balance, and uterine contractions in childbirth? (10.2) K/U
   (a) parathyroid
   (b) posterior thyroid
   (c) pineal
   (d) posterior pituitary
10. Which hormone is secreted by the posterior lobe of the pituitary gland? (10.2) K/U
    (a) ADH
    (b) TSH
    (c) ACTH
    (d) FSH
11. What is a symptom of diabetes mellitus? (10.3) K/U
    (a) abnormal mineral absorption
    (b) low level of blood calcium
    (c) low glucose content in urine
    (d) high glucose content in urine
12. Which hormone is a synthetic steroid hormone? (10.5) K/U
    (a) cortisol
    (b) testosterone
    (c) nandrolone
    (d) norepinephrine
13. Which of the following is a role of LH in the female body? (10.7) K/U
    (a) It stimulates the production of TSH.
    (b) It regulates mineral metabolism.
    (c) It stimulates uterine contractions.
    (d) It promotes progesterone production.

14. Which term refers to the component of the neural signalling pathway in which messages are sorted and interpreted? (11.1) K/U
    (a) response
    (b) integration
    (c) reception
    (d) action
15. For a neuron, the outside of the plasma membrane has a higher concentration of what compared to the inside? (11.2) K/U
    (a) Na^+
    (b) K^+
    (c) Ca^{2+}
    (d) anions
16. Which of the following is a protective covering of the brain? (11.3) K/U
    (a) ventricles
    (b) reflexes
    (c) thalamus
    (d) meninges
17. Which statement about the sympathetic and parasympathetic divisions of the nervous system is correct? (11.4) K/U
    (a) The sympathetic system is under voluntary control, while the parasympathetic system is under involuntary control.
    (b) The sympathetic system controls external stimuli, while the parasympathetic controls internal stimuli.
    (c) The sympathetic system generally produces increased physical activity, while the parasympathetic system produces a decrease in physical activity.
    (d) Both systems release norepinephrine.
18. Some spicy foods, such as jalapeño peppers, contain the chemical capsaicin. If you lacked the nociceptors that bind capsaicin, what would be the predicted outcome? (11.5) K/U A
    (a) You would be able to eat foods that contain high concentrations of capsaicin and not feel any burning in your mouth.
    (b) You would have the same sensitivity to capsaicin as most other people.
    (c) You would experience a feeling of cold when eating foods that contain capsaicin.
    (d) You would be especially sensitive to foods that contain capsaicin.
19. What is the correct order of the three stages of Selye's general adaptation syndrome? (11.6) K/U
    (a) resistance, alarm, exhaustion
    (b) exhaustion, alarm, resistance
    (c) alarm, resistance, exhaustion
    (d) alarm, exhaustion, resistance

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

20. The reproductive system is not required for the maintenance of homeostasis within an organism. (9.1) K/U
21. Sweating in response to elevated temperature is an example of a stimulus of negative feedback. (9.2) K/U
22. The physiological changes that help ectotherms adapt their temperature tolerance as the seasons change from winter to summer are called thermal acclimatization. (9.3) K/U
23. Osmoregulation ensures that intracellular and extracellular fluids are hyperosmotic. (9.4) K/U
24. Nephrons are found in flatworms. (9.5) K/U
25. Estrogen, progesterone, and cortisol are all examples of steroid hormones. (10.1) K/U
26. The thyroid gland secretes hormones that help to regulate biological rhythms by producing the hormone melatonin. (10.2) K/U
27. The adrenal cortex produces glucocorticoids that help to regulate the blood sugar level. (10.2) K/U
28. Many of the hormones found in vertebrates may also be found in invertebrates, although their functions may differ. (10.2) K/U
29. Type 2 diabetes must be treated by injections of insulin. (10.3) K/U
30. Natural steroid hormones occur in the human body and control both male and female sexual development and reproduction, the adrenal fight-or-flight response, and the level of blood glucose. (10.5) K/U
31. FSH is released in the adrenal glands in response to gonadotropin-releasing hormone from the hypothalamus. (10.7) K/U
32. Glial cells are a special type of Schwann cells, which produce the myelin sheath. (11.1) K/U
33. The re-establishment of polarity in neurons is called propagation. (11.2) K/U
34. White matter centred in the pons and the medulla controls involuntary functions such as heart rate and blood pressure. (11.3) K/U
35. There are 21 pairs of spinal nerves. (11.4) K/U
36. Sensory adaptation is the tendency for some sensory receptors to become less sensitive when stimulated repeatedly. (11.5) K/U
37. Stress is the body's response to stimuli that cause a disruption in homeostasis. (11.6) K/U

Match each term on the left with the most appropriate description on the right.

38. (a) urea
    (b) water
    (c) reabsorption
    (d) glomerulus
    (e) nephron
    (f) diffusion
    (g) filtration
    (h) bladder
    (i) active
    (j) distal

    (i) ball of capillaries in the head of a nephron
    (ii) smooth muscular bag that collects urine before it is released from the body
    (iii) waste that is produced in the liver by the deamination of amino acids
    (iv) portion of the convoluted tubules where secretion occurs
    (v) substance that is reabsorbed from the collecting duct when the body needs it
    (vi) process in which nutrients and water move from the proximal convoluted tubule to blood vessels
    (vii) functional microscopic units of the kidney
    (viii) movement of glucose into the blood vessels from kidney tissue
    (ix) forced movement of fluid and small materials into the Bowman's capsule
    (x) type of transport that moves many materials out of the convoluted tubules (9.4. 9.5) K/U

39. (a) insulin
    (b) MSH
    (c) oxytocin
    (d) epinephrine
    (e) calcitonin

    (i) produced in anterior pituitary gland
    (ii) produced in posterior pituitary gland
    (iii) produced in adrenal gland
    (iv) produced in thyroid gland
    (v) produced in pancreas (10.2) K/U

40. (a) Na^+ and K^+
    (b) action potential
    (c) resting potential
    (d) sodium–potassium pump
    (e) refractory period

    (i) interval in which a membrane returns to resting potential after repolarization
    (ii) steady voltage difference across a membrane, usually –70 mV
    (iii) brief reversal in the voltage across a membrane
    (iv) mechanism by which ion concentrations across a membrane are maintained
    (v) two ions that are used in the generation of an action potential across a membrane (11.2) K/U

Write a short answer to each question.

41. What makes up the internal environment of the human body? (9.1) K/U

42. Is the fight-or-flight response a positive or a negative feedback response? Why? (9.2) K/U

43. (a) How are hibernation and estivation similar?
    (b) How are hibernation and estivation different? (9.3) K/U

44. (a) What is deamination?
    (b) Why is deamination an important process? (9.4) K/U

45. Copy and complete **Table 1**. (9.5) K/U

Table 1

Structure	Process	Description	Molecules present
Bowman's capsule	filtration	movement of fluids from the glomerulus into Bowman's capsule	
proximal tubule			active transport of glucose, amino acids, sodium; osmosis of water
distal tubule		movement of molecules from the blood to the nephron	uric acid, ammonia, H^+ ions
collecting duct	excretion		water, salts, urea, uric acid

46. (a) What does ACE stand for, in the context of ACE inhibitors?
    (b) When are ACE inhibitors normally used? (10.1) K/U

47. Explain the terms "target" and "gland" as they are used for the endocrine system. (10.2) K/U

48. Epinephrine and norepinephrine are sometimes referred to as stress hormones because they prepare the body for emergency responses. List four physiological changes that result from the release of these hormones. (10.2, 11.6) K/U

49. Copy and complete this sentence: A person who has a normal blood sugar level but urinates frequently, producing a large volume of urine daily, is probably suffering from ________, which is caused by a deficiency in the hormone ________. (10.3) K/U

50. Why are anabolic steroids not used in primarily aerobic sports? (10.5) K/U

51. Copy and complete this sentence: Ovulation occurs when the ________ gland secretes high levels of ________. (10.7) K/U

52. Identify the three types of neurons that are involved in a reflex arc. List the neurons in the order they are used to complete the arc. (11.1) K/U

53. A diagram of a neuron is shown in **Figure 1**.

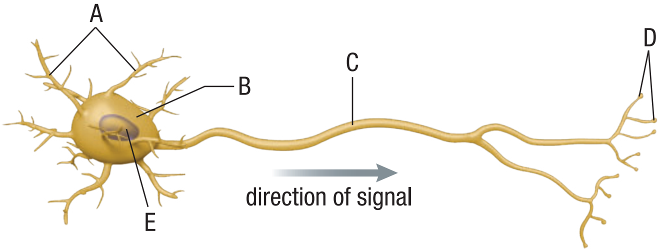


Figure 1

(a) Identify the labelled structures (A–E) of the neuron.
(b) Copy and complete this sentence: If this were a motor neuron, it would relay signals from the ________ or ________ to ________ and ________.
(c) Which part of the neuron receives the electrical impulse?
(d) What is the function of structure D in the diagram? (11.2, 11.3) K/U

54. Which part of the brain plays a major role in motor responses or voluntary movements of the skeletal muscles, and is therefore responsible for balance and fine motor control? (11.3) K/U

55. When stimulated, a band of grey matter in the spinal cord produces a neurotransmitter that results in pain perception. What is the name of this band of grey matter? (11.4) K/U

56. Which photoreceptors in the eye are specialized for the detection of different wavelengths (colours)? (11.5) K/U

Understanding

57. Which body system regulates the concentrations of oxygen and carbon dioxide? (9.1) K/U

58. Why does the body change the set point of its body temperature? Give an example. (9.2) K/U

59. According to what we know about diffusion, the concentrations of ions inside and outside a cell should be the same. In a neuron, however, the concentrations of sodium and potassium ions are quite different. How does the cell counter the forces of diffusion? (9.4, 11.2) K/U

60. Why do many marine animals not need to osmoregulate? (9.4) K/U

61. Use **Figure 2** to answer the following questions. (9.5) K/U

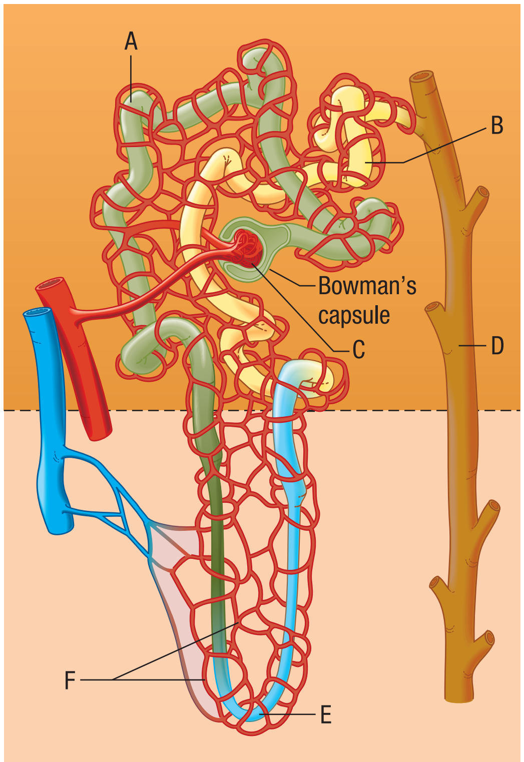


Figure 2

(a) Which structures are shown in the diagram?
(b) Where would you expect to find glomerular filtrate that is most similar to the excreted urine?
(c) Where would you expect to find blood with the greatest concentration of urea?
(d) What happens to most of the water that passes into the glomerular filtrate?
(e) Explain how an increase in blood pressure in area C would affect the functioning of the kidney.
(f) What substance would you normally find in area A but not in area E?
(g) What substance would you normally find in area C but not in area A?

62. What is a prohormone? (10.1) K/U

63. Sketch and label a flow chart for the negative feedback loop used by calcitonin. Include directional arrows. (10.1, 10.2) K/U C

64. Antidiuretic hormone (ADH) is listed as a pituitary hormone, but it is not produced in the pituitary gland. Where is ADH produced, and how does it get to the pituitary gland? (10.2) K/U

65. Explain the role of the pituitary gland in the development and maintenance of the secondary sexual characteristic in males. (10.2, 10.7) K/U

66. List three conditions that can be treated by synthetic hormones. (10.5) K/U

67. Put the following events in the correct order to explain the withdrawal reflex response. (11.1) K/U
   (a) The afferent neuron transmits the impulses to the spinal cord.
   (b) The other efferent neuron stimulates the flexor muscle to contract.
   (c) Interneurons integrate the information.
   (d) Your finger touches a hot test tube.
   (e) The flexor muscle contracts, withdrawing your hand.
   (f) A pain receptor in your finger stimulates an afferent neuron.
   (g) One efferent neuron stimulates the flexor muscle, causing it to contract.

68. Which lobe of the brain is responsible for vision? (11.3) K/U

69. What does the autonomic nervous system control? (11.4) K/U

70. Opiates reduce pain because their structure is similar to the structure of endorphins. (11.5) K/U
   (a) What are endorphins?
   (b) How do endorphins reduce pain in the body?

Analysis and Application

71. How do birth control pills that contain artificial hormones reduce the chances of pregnancy? (9.2, 10.2, 10.7) K/U T/I

72. While humans are not endotherms, one of our responses to cold is shivering. How does shivering help the body thermoregulate? (9.3) K/U A

73. Predict how a drop in blood pressure would affect urine production. Provide reasons for your answer. (9.5) K/U T/I

74. Use **Table 2** to answer the following questions, and explain your answer for each one. (9.5, 10.3) K/U T/I A
   (a) Which sample is from a patient who has diabetes mellitus? Explain your answer.
   (b) Which sample is from a patient who has diabetes insipidus? Explain your answer.
   (c) Which sample is from a patient who has Bright's disease? Explain your answer.

Table 2

Sample	Glucose (g/L)	Protein (g/100 mL)	Urea (g/100 mL)
A (normal)	0.1	0	2.0
B	2.3	0	2.2
C	0.2	5.1	1.9
D	0.1	0	0.002

75. Syphilis is a sexually transmitted infection that can destroy the high-pressure capillaries of the glomerulus. These capillaries are responsible for the formation of filtrate in the nephron when proteins and other large molecules enter the filtrate. Once these capillaries are destroyed, they cannot be repaired. A person who contracts syphilis may require dialysis and eventually a kidney transplant. (9.5) K/U T/I A
   (a) How does the filtrate form in the nephron under normal conditions?
   (b) How would this be different in a person with syphilis?
   (c) How could dialysis be used to treat a person with kidney failure?
   (d) Do you believe that all patients who need a kidney transplant should be given the same priority, regardless of how they came to require the transplant? Explain your reasoning.

76. After consuming a large amount of alcohol, many people suffer from a hangover the next day. One of the symptoms of a hangover is dehydration. Explain why a person would be dehydrated after consuming alcohol. (9.5, 10.2) K/U A

77. The solutes that are found in the filtrate from a nephron are analyzed to determine if the nephron is functioning properly. The data are given in **Table 3**. All quantities in Table 3 are recorded in g/100 mL. (9.5) K/U T/I

Table 3

Solute/ substance	Bowman's capsule	Glomerulus	Loop of Henle	Collecting duct
protein	0	0.95	0	0
urea	0.03	0.03	1.35	2.10
glucose	0.15	no data	0	0
chloride	0.28	no data	no data	0.65
ammonia	0.0003	0.0003	0.0003	0.06
unknown substance	0	9.75	0	0

   (a) Which solute was not filtered by the nephron? Explain your answer.
   (b) What could the unknown substance be? Why?
   (c) Why do urea and ammonia levels increase after filtration occurs?
   (d) Based on the data in Table 3, what part of the nephron is the area that ADH would act on?

78. A pregnant woman visits her doctor, complaining of tiredness, excessive thirst, and frequent urination. A blood test shows a rapid rise in blood sugar after eating. (10.3) K/U
   (a) What is she most likely suffering from?
   (b) Why do you think the rapid rise in blood sugar occurs only after eating?
79. In an experiment using an isolated motor neuron, researchers observed that a minimum level of stimulation was needed to initiate a response. If a stronger stimulus was applied, there was no increase in the magnitude of the response or the speed of the response. Regardless of the stimuli, the amplitude and duration of the action potential were the same. (11.2) K/U A
   (a) What principle do these observations demonstrate?
   (b) What does this principle depend on?
80. Neurons are classified as either excitatory or inhibitory. Excitatory neurons release neurotransmitters that stimulate other neurons. Inhibitory neurons release neurotransmitters that have the opposite effect. Why are both types of neurons necessary? (11.2) K/U T/I A
81. A classmate uses the terms “nerve” and “neuron” interchangeably. Is your classmate correct? Are a nerve and a neuron the same thing? Explain. (11.2) K/U A
82. Chocolate contains chemicals that decrease stress, lessen pain, and relieve depression. Which neurotransmitters do the chemicals likely stimulate to have these effects? (11.2) K/U T/I A
83. While on vacation in Mexico during spring break, a student developed a severe ear infection. After treatment, the doctor said that the student could not fly home until the infection was gone. Explain why the doctor would say this. (11.5) K/U T/I A
84. Many people complain that food does not taste as good when they have a cold as it does when they are healthy. Explain this complaint. (11.5) K/U T/I A
85. Why is a small daily dose of acetylsalicylic acid (ASA) sometimes prescribed to reduce the risk of heart attack or stroke? (11.6) K/U A

Evaluation

86. Imagine that you are studying first-year biology at a university. A friend in your class tells you that homeostasis is actually bad for the body. Your friend argues that most diseases cause a homeostatic imbalance. Sometimes, to re-establish homeostasis, the body creates problems that compound a condition. Based on what you have learned about homeostasis in this unit, explain why your friend is not considering all sides of the issue. Use examples to support your explanation. (9.1, 9.2) K/U T/I A
87. Why are blood glucose levels important for overall human health? (9.1, 10.2, 10.3) K/U T/I A
88. Suppose that you are developing an experiment in which you will use two rats to determine the structure responsible for the regulation of water balance. Consider an experimental design that would study the removal of the pituitary gland of one of these rats. In your experimental design, include the following:
   - testable question
   - hypothesis
   - independent, dependent, and controlled variables (9.5, 10.2) K/U T/I A
89. A patient is suffering from the following symptoms:
   - increase in heart rate
   - increase in blood pressure
   - hyperglycemia
   - dilation of the pupils
   - cool, pale skin

   The doctor believes these symptoms are hormone related. (10.2, 11.6) K/U T/I A
   (a) Based on the information provided, which endocrine gland and which hormone are likely involved? Explain your reasoning.
   (b) What might the diagnosis be?
90. A friend comments that she has stopped growing so she is no longer producing growth hormone. (10.2) K/U T/I A
   (a) Is your friend correct, or does her body still need GH?
   (b) What would you tell your friend? Support your response with examples.
91. Some foods, such as processed soy (**Figure 3**), have chemicals that are similar to human estrogen. Some sources caution young males to avoid eating large amounts of soy-based foods. Predict the effects of environmental estrogens on males during puberty. (10.2, 10.7) K/U T/I A

Figure 3

92. Acetylcholinesterase is an enzyme that breaks down the neurotransmitter acetylcholine into acetic acid and choline. Why do you think acetylcholine has an enzyme that breaks it down? (11.2) K/U T/I A

93. The drug atropine inhibits parasympathetic activity. Predict why an ophthalmologist would use this drug when examining the interior of a patient's eye. (11.4) K/U T/I A

94. Imagine that you are an organ in a human body system. Write a fairy tale, from your point of view, about how the super-hero Homeostasis got rid of your system's arch-enemy and saved the day for your system. Be sure to describe all the functional parts or processes of your system, as they relate to the story. (Chapters 9, 10, 11) K/U T/I C A

95. Create a poem about any system that was discussed in this unit. Focus on the interaction of the hormones involved with this system. Your poem should be a minimum of four verses, each with four lines, and can be rhyming or free verse. (Chapters 9, 10, 11) K/U T/I C A

Reflect on Your Learning

96. Based on what you have learned in this unit, why is homeostasis important for maintaining good health? K/U T/I

97. Some neurotransmitters have an inhibitory effect; that is, they prevent the transmission of impulses. Why do you think the inhibitory effect is important to you as you sit writing an answer to this question? K/U T/I A

98. Pre-employment urine drug testing is becoming a more common hiring requirement. While many prospective employees are not pleased with this, employers argue that drug testing lessens tardiness, absenteeism, turnover, attitude problems, theft, decreased productivity, crime, and violence in the workplace. T/I
    (a) How do you feel about drug testing as a hiring requirement?
    (b) Do you think that a company has a right to use the results of drug tests as part of the application process? Should there be a provisional offer of a job before drug testing is required? Explain your reasoning.
    (c) Should all employees in any job be subject to drug testing, or should only some jobs require drug testing? If so, which jobs and why?
    (d) Would you be willing to take a drug test to get a job? Explain your reasoning.

99. Anti-doping researchers are constantly looking for new ways to catch athletes who use performance-enhancing drugs or illegal biological methods. Confronted with increasingly sophisticated doping techniques, these researchers face a daunting task. An anti-doping laboratory in Switzerland has pioneered a new kind of anti-doping test: a biological passport. Instead of testing urine samples for traces of drugs or products of the breakdown of drugs, a drug passport builds a profile of an individual over time, and tries to detect biochemical changes that might indicate doping. Since 2008, the International Cycling Union has created biological passports for hundreds of professional cyclists, some using multiple blood samples taken over time.

    Some researchers think that this type of testing is their best way to detect EPO doping, a problem that has challenged them for many years. Some athletes think that a biological passport is laughable, however, and that athletes knew how to defeat it before it was even available. Nevertheless, it seems to be working for now. K/U T/I A
    (a) Do you think that a biological passport, created with multiple samples, is better than random urine samples for discouraging drug use in professional sports? Why or why not?
    (b) Do you think that it is realistic to expect the science of anti-doping to match the creation or development of performance-enhancing drugs and masking agents? Explain your thinking.
    (c) The career of a professional athlete may range from 5 to 15 years, depending on the sport and the age of the athlete. Do you think that a two-year ban for a first doping offence is reasonable? Why or why not?
    (d) The World Anti-Doping Agency (WADA) code has only two penalties, and they apply only to doping violations. The penalty for a first offence is a two-year ban, and the penalty for a second offence is a lifetime ban. Do you think that a lifetime ban for a second offence is an appropriate punishment? Explain your thinking.

Research

WEB LINK

100. Scientists have been working with stem cells to develop cures or treatments for severe spinal cord injuries. Conduct research to find out why stem cells are being used for these studies and how stem cells could be used to cure paralysis if the studies are successful. Write a half-page report on your findings. K/U T/I C A

101. If you have ever known someone who has had kidney stones (**Figure 4**), you have undoubtedly been told that they are extremely painful as they pass through the urethra. Using the Internet and other sources, find answers to the following questions. Use your answers to create a fact sheet about kidney stones to share with your classmates.
- What is a kidney stone?
- What causes a kidney stone?
- What are the signs and symptoms of kidney stones?
- How is the presence of kidney stones diagnosed?
- What are the treatment options?
- How can kidney stones be prevented?
- If a person has chronic kidney stones, why might a doctor recommend not consuming alcohol?
- Kidneys stones used to be a condition associated with aging, but doctors are reporting a steep increase in kidney stones in children. What do doctors believe is the reason for this increase? K/U T/I C A

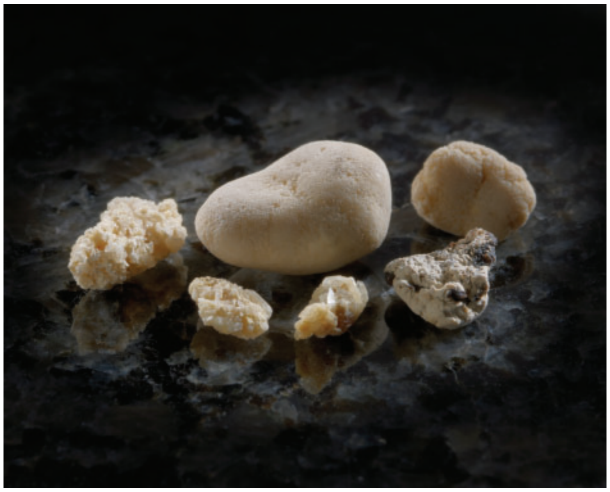


Figure 4

102. Endocrine system disorders result from too much or too little of a hormone, or sometimes from no hormone at all. Osteoporosis is a disorder that is treated by endocrinologists. Using the Internet and other sources, find out as much as you can about osteoporosis and the hormones that play a role in this bone disease. Prepare a one-page report that answers the following questions:
- What is osteoporosis?
- In what age range does osteoporosis generally occur?
- What hormones are involved in osteoporosis?
- Who is at risk for osteoporosis?
- What factors can increase your risk for bone loss?
- What can you do to avoid osteoporosis?

K/U T/I C A

103. Amphetamines, such as methamphetamine, act on the pleasure circuit by altering the levels of neurotransmitters that are present in the synapse. Scientists are currently studying the long-term effects of chronic methamphetamine abuse in humans. Research with laboratory animals has demonstrated that exposure to a single high dose of methamphetamine or prolonged exposure to low doses destroys up to 50 % of the dopamine-producing neurons in certain parts of the brain. Although the damage of chronic methamphetamine abuse may not be immediately apparent in humans, scientists believe that the progressive decrease in the number of dopamine-producing neurons may lead to symptoms of Parkinson's disease. Using the Internet and other sources, research how amphetamines affect the transmission of nerve impulses in the four lobes of the brain. Create a poster to share your findings.

K/U T/I C A

104. The human brain appears to be split down the middle into two distinct divisions: a right hemisphere and a left hemisphere. These hemispheres communicate with each other through a thick band of 200 million to 250 million nerve fibres, called the corpus callosum, as well as smaller bands of fibres called commissures. Each hemisphere seems to be specialized for certain behaviours and functions and has developed to perceive life experiences quite uniquely. The primary duty of the right side of the brain is to control muscles on the left side of the body. The primary duty of the left side of the brain is to control muscles on the right side of the body. Also, sensory information from the left side of the body crosses over to the right side of the brain, and information from the right side of the body crosses over to the left side of the brain.

Occasionally, neurosurgeons have patients who require either a functional hemispherectomy or an anatomical hemispherectomy, although the functional hemispherectomy is usually the operation of choice. Using the Internet and other sources, find out when and why these operations are used. Write a one-page report, using the following questions as a guide:
- What are functional and anatomical hemispherectomies?
- What condition do surgeons use these operations for?
- Who is a candidate for a functional hemispherectomy?
- What happens before, during, and after a functional hemispherectomy?
- How effective is this operation?
- What are the side effects of this operation?

K/U T/I C A

UNIT 5

Population Dynamics

OVERALL EXPECTATIONS

- analyze the relationships between population growth, personal consumption, technological development, and our ecological footprint, and assess the effectiveness of some Canadian initiatives intended to assist expanding populations
- investigate the characteristics of population growth, and use models to calculate the growth of populations within an ecosystem
- demonstrate an understanding of concepts related to population growth, and explain the factors that affect the growth of various populations of species

BIG IDEAS

- Population growth follows predictable patterns.
- The increased consumption of resources and production of waste associated with population growth result in specific stresses that can affect Earth's sustainability.
- Technological developments can contribute to or help offset the ecological footprint associated with population growth and the consumption of natural resources.

UNIT TASK **PREVIEW**

In the Unit Task, you will consider the relationship between the growing human population and the abiotic or biotic environment. You will assess one aspect of this relationship and its implications for the future as the human population continues to grow. The Unit Task is described in detail on page 688. As you work through the unit, look for Unit Task Bookmarks to see how information in the section relates to the Unit Task.

GREEN CITIES

A recent scientific study is raising concerns about the impact of urban expansion on the global environment. Researchers from Yale, Arizona State, Texas A&M, and Stanford universities predict that by 2030 urban areas will expand by 1.5 million km^2. In addition, they predict that by 2050 80 % of the world population will live in urban areas. Conservative estimates suggest that the world population will increase by three billion people between now and then.

One problem created by our increasing population and urban expansion is that we are growing increasingly short of productive farmland. One way to solve this problem is to alter the way that we think about traditional farming and to create new ways of meeting the demand for food.

One of the most fascinating proposals is a concept called vertical farming. This efficient alternative to flat farming involves growing plants or raising animals in skyscrapers or vertically inclined surfaces. Using greenhouse technology, such as hydroponics and aeroponics, vertical farms could produce not only fruit and vegetables, but also poultry and fish. Proponents of vertical farming believe that these “skyfarms” or “farmscrapers” could be both economically and environmentally feasible. They would reduce the energy costs of transporting food over long distances and release less atmospheric carbon dioxide (a greenhouse gas responsible for climate change). Vertical farms are not just a dream for the future. Several vertical farms have been built since 2010 in Japan, Korea, the Netherlands, and England.

A proposed plan for a skyfarm in Toronto’s theatre district has 58 floors, 250 000 m^2 of floor area, and 740 000 m^2 of growing area. This skyfarm could operate year-round and would be protected from disease, climate variability, and pollution. It could produce as much as a 400 ha (hectare) farm and feed 35 000 people each year. In addition, it would use renewable energy sources, such as wind and solar power, as well as recycled materials of production, such as water. Vertical farming could become an innovative way to create sustainability and greener cities around the world.

Questions

1. What features of your community make it a pleasant place to live? What features make it less pleasant?
2. Is the human population in your community increasing? What about the populations of other species?
3. What are the advantages of a significant change in population size? Are there disadvantages? Explain your reasoning.
4. What changes to natural biotic and abiotic factors make most urban areas unsuitable for growing food? How might these changes be overcome by vertical farms?
5. What do you think makes a community “green”? What innovative green environmental technologies or approaches do you see in your community? What green approaches would you like to see?

UNIT 5 ARE YOU READY?

CONCEPTS

- recognize the structure and function of food webs
- understand trophic relationships
- distinguish between carrying capacity, habitat, and niche
- identify biotic and abiotic factors
- contrast endangered species and invasive species
- describe interactions such as symbiosis, mutualism, commensalism, and parasitism

SKILLS

- plot data on simple graphs, such as histograms and line or scatter plots
- interpret a graph with two vertical axes and two curves, including the relationship between the two curves
- solve equations that are similar to the logistic equation
- describe key components of a scientific journal article

Concepts Review

1. Decide whether each statement is true or false. If you think the statement is true, copy it directly into your notebook. If you think the statement is false, rewrite it to make it true. K/U
   (a) All the members of the same species living in the same ecosystem or habitat are referred to as a population.
   (b) In a food chain, energy flows from a secondary consumer to a primary consumer to a producer.
   (c) Every time that energy is transferred within an ecosystem, some of the energy changes form.
   (d) The carrying capacity is the minimum number of individuals that can be supported indefinitely by an ecosystem.
   (e) An ecological niche is defined as the conditions required for the survival of a species.
   (f) An extirpated species is a species that is close to extinction.
   (g) A rapid increase in a population always indicates that the ecosystem is healthy.
   (h) An invasive species can have a beneficial impact on an ecosystem.
2. Match each term on the left with the most appropriate description on the right. K/U
   (a) symbiosis
   (b) parasitism
   (c) commensalism
   (d) mutualism

   (i) a relationship between species in which one species benefits and the other species is unaffected
   (ii) an interaction between two species that live in close association with each other
   (iii) a relationship between species in which one species benefits by living and feeding in or on the other species
   (iv) a relationship between species in which both species benefit
3. (a) Compare and contrast food chains and food webs. Sketch an example of each.
   (b) How are food webs related to the concept of trophic levels? K/U T/I C
4. Explain what happens to the available energy as you move up through the trophic levels in an ecosystem. How does this affect population numbers? K/U
5. (a) Define the terms "biotic factor" and "abiotic factor."
   (b) Give two examples of how biotic factors can affect the abiotic factors of an ecosystem.
   (c) Give two examples of how abiotic factors can affect the biotic factors of an ecosystem. K/U T/I
6. How would studying a population provide information about a species that cannot be gained by studying an individual? K/U T/I
7. What information would biologists learn by conducting a comparison study of populations of the same species living in different locations? T/I
8. In a report on invasive species, a scientist noted that zebra mussels have displaced species of native mussels that occupy similar ecological niches. The scientist also noted that zebra mussels have had a very serious impact on species that do not share the same ecological niche. K/U T/I A
   (a) Explain why it is not surprising that an invasive species can cause harm to a native species that occupies the same ecological niche.
   (b) Explain how an invasive species can have a negative impact on species with entirely different niches.
9. In a prairie ecosystem, primary consumers have 100 000 units of energy in their biomass. Determine the maximum quantity of energy that tertiary consumers in that ecosystem could have. Explain how you determined this. K/U T/I

10. (a) Explain the difference between density-dependent factors and density-independent factors.
    (b) Classify the following factors as either density-dependent or density-independent. K/U T/I
        (i) food shortage
        (ii) increased predation
        (iii) forest fire
        (iv) climate change
        (v) destruction of habitat
        (vi) competition for mates
        (vii) drought
        (viii) introduction of an invasive species

11. Calculate the change in a population of 950 lemmings after the following data were collected. Show your work. T/I

births = 255
deaths = 103
immigration = 6
emigration = 9

12. Is the white-tailed deer population of Ontario an open population or a closed population? Explain your answer. T/I

Skills Review

13. A culture of *Lactobacilli* that is being used to produce yogurt is doubling every 3 h (**Figure 1**). T/I

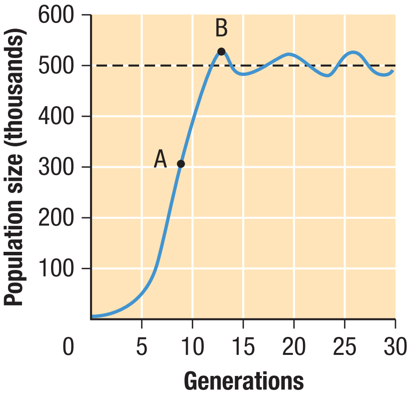


Figure 1 Population growth of a *Lactobacilli* culture

    (a) What is happening to the population of *Lactobacilli* up to point A?
    (b) What happens at point B? Describe what you think is happening after point B, and explain why.
    (c) What is the carrying capacity of this population?

14. A northern pike population in a portion of Lake Erie was monitored over a seven-year period. The data collected are shown in **Table 1**. T/I C

Table 1 Changes in Adult Northern Pike Population

Year	Population
2005	10 000
2006	13 000
2007	15 000
2008	16 000
2009	12 000
2010	11 000
2011	11 000

    (a) Graph the changes in the adult northern pike population. Label the axes, and give your graph an appropriate title.
    (b) Describe and explain the growth that is illustrated by your graph.
    (c) Give two possible explanations for the lack of population growth in 2009, 2010, and 2011.
    (d) Suggest a possible reason or reasons why these scientists monitored adults instead of the entire population.

15. Scientific journals are used to present new research. The research articles in these journals have specific sections, which are presented in a particular order. K/U
    (a) List the following sections of a research paper in the correct order:
        - Introduction
        - Results
        - Conclusions
        - Abstract
        - Discussion
        - Methodology
    (b) Write a brief description of each section.

CAREER PATHWAYS **PREVIEW**

Throughout this unit you will see Career Links. Go to the Nelson Science website to find information about careers related to population dynamics. On the Chapter Summary page at the end of each chapter, you will find a Career Pathways feature that shows you the educational requirements of the careers. There are also some career-related questions for you to research.

CHAPTER 12 Natural Population Dynamics

KEY CONCEPTS

After completing this chapter you will be able to

- describe how abiotic and biotic factors play a role in determining the size, density, and distribution of a population
- explain how population growth follows different trends, such as exponential and logistic trends
- discuss how density-dependent factors, such as competition and predation, affect population size and growth
- describe how density-independent factors, such as natural disasters, affect population size and growth
- explain how reproductive strategies vary among organisms and affect population growth

What Factors Influence the Size, Distribution, and Growth of Natural Populations?

Populations of organisms are dynamic and ever-changing, influenced by many factors. For example, the size of a population may change as a result of human activities. Some polar bear populations (*Ursus maritimus*) are declining, partly because of habitat loss due to climate-change induced melting of sea ice. Other species, such as the once-native elk (*Cervus elaphus*) have been intentionally re-introduced into Ontario after disappearing in the nineteenth century due to over-hunting. While the elk are slowly adapting to their new home, there are some unintentional consequences, including the introduction of new diseases and threats to farm crops. Our own human population has experienced continuous growth since the early fourteenth century and reached seven billion by the end of 2011.

Populations are also affected by natural factors. For example, giant hogweed (*Herecleum mantegazzianum*) is an invasive species that has appeared on roadsides and riverbanks in southern Ontario. In Europe, this plant has caused the erosion of riverbanks, threatening populations of salmon who spawn in the rivers.

Some species are widespread, whereas others have a narrow distribution. For example, barn owls (*Tyto alba*) are found on every continent except Antarctica. Lemurs (*Lemuridae*), however, live only on the island of Madagascar, off the east coast of Africa. Primates in this family, which includes 10 species, look like a cross between a cat, a dog, and a squirrel. Approximately 160 million years ago, continental drift separated Madagascar from the continent of Africa and geographically isolated the lemurs.

Why do populations change? What factors play a role in determining the size, density, and distribution of a population? In this chapter, you will learn about the methods that biologists use to study and monitor natural populations, focusing on the specific factors that influence population size and distribution.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Populations vary in many ways, including the number of individuals, how the individuals are distributed through the area, and whether the total number of individuals is increasing or decreasing. Brainstorm some of the methods that biologists might use to gather information about population.
2. What factors do you think are most likely to affect the size of a population? Which of these factors might cause the size of a population to change rapidly?
3. Many factors affect the size and structure of a population. What are some of the ways that humans could affect a population, either negatively or positively?
4. Could a population continue to grow indefinitely? What are some of the possible limits to the growth of a population?

Mini Investigation

Performing Random Sampling

Skills: Performing, Observing, Analyzing

SKILLS HANDBOOK **A2.1**

Biologists usually cannot count every organism in a population. One method they use to estimate the size of a population is to collect data from a random sample. They use a random sample because each individual in a population has an equal chance of being counted, ensuring that the data are not biased. In this investigation, you will compare the data collected through random sampling to the actual population size.

Equipment and Materials: envelope containing a model sampling plot of a salamander population

1. Pull a sample square from the envelope. Count the number of salamanders in this square and record the data in a table.
2. Pull nine more sample squares from the envelope. For each, count and record the number of salamanders in the square.
3. Use this data to estimate the total size of the population. Assume that the 10 sample squares represent 10 % of the total population.
4. Repeat the process two more times. Use this data to refine your estimate based on 30 % of the total population size.

A. Compare your estimated population size (based on your samples) with the true population size. How close are they? T/I

B. Why do biologists use sampling, instead of counting all the individuals in a population? T/I

C. How effective was the sampling process? Suggest some possible populations that might make this form of sampling less effective, and explain why. T/I

12.1 Population Characteristics

White-tailed deer (*Odocoileus virginianus*) are becoming more and more common in some cities in southern Ontario. Urban infringement on natural habitats, increased traffic, and changes in agricultural land-use practices have all increased interactions between the deer and humans (**Figure 1**). The increasing presence of white-tailed deer within city limits is problematic for both the deer and humans. Crop damage and a growing number of collisions between deer and drivers have encouraged government and wildlife officials to initiate strategies to maintain healthy deer populations (groups of the same species living in a particular geographic area at the same time) and reduce conflicts between the deer and humans.

Figure 1 White-tailed deer are becoming more common in urban areas. Fish and wildlife officers monitor deer populations to maintain healthy, sustainable levels.

Some people see the deer as destructive because the deer may damage crops or create a hazard on roadways. They believe that culling the population (selectively removing some of its members) is necessary. This was accomplished, in part, by a selective harvest system that was implemented in the 1980s to maintain healthy, sustainable deer populations. However, other people recognize that interactions with the deer are part of our relationship with nature. They believe that we should value the integrity and beauty of nature, rather than regard nature as something to manage.

Monitoring wildlife and protecting the rich biodiversity of the province while providing ecological resources is part of the mandate of the Ontario Ministry of Natural Resources. Wildlife officers monitor populations to determine if a species is invasive or if it is a native species expanding its range because of human activities. They need to decide what population size is ideal for a particular habitat and know when a population has reached this ideal size. They must also maintain healthy, sustainable population levels, using the many wildlife management options that are available.

CAREER LINK

population ecology a sub-field of ecology that focuses on the dynamics of populations and how populations interact with their environment

Population ecology is the study of populations, particularly their size, density, distribution, and changes over time. Population ecologists monitor, evaluate, and model changes in populations. By doing this, they are able to gather data that can help them predict growth trends in populations. The data can also help them determine the health of the different species and the ecosystems in which the species live. This information then allows scientists to manage the size of the populations. Research in ecology is often linked to work in genetics, physiology, anatomy, behaviour, palaeontology, and evolution, as well as geology, geography, and environmental science. Many ecological phenomena, such as climate change, occur over huge areas and long time spans, so ecologists must devise ways to determine how environments influence organisms and how organisms change the environments in which they live.

The Distribution of Populations

The distribution of a population is described by three key factors: its geographic range, defined by various boundaries; its population size and density; and the way that individuals are dispersed through the area.

Geographic Range

geographic range the overall spatial boundaries within which a population lives

The **geographic range** is the total area that is occupied by a population. Geographic ranges vary enormously. The lakeside daisy (*Hymenoxys herbacea*), for example, is a rare species in the aster family that lives only in the Great Lakes region. It is found in Michigan, Ohio, Illinois, and southern Ontario. In Ontario, 38 populations of this species are found in the southern part of Manitoulin Island and on the Bruce Peninsula. Conversely, the tamarack larch (*Larix laricina*) has a very extensive geographic range. This tree is native to northern North America and can be found in all the provinces and territories of Canada.

habitat the place where an organism normally lives

A **habitat** is a specific environment in which an organism lives. It is characterized by its biotic and abiotic features. The common blue violet (*Viola sororia*), for example, grows in shaded fertile habitats, where moist soil is prevalent. Since the violet grows low to the ground, it tends to creep into lawns and gardens. Despite its pretty blooms, it is often considered to be a weed. In contrast, the lakeside daisy is mainly found in alvar habitats (limestone bedrock with thin or no soil). These habitats are threatened by quarry and cottage development, as well as increased recreational usage. This flower has been designated as a threatened species in an effort to stop its population from declining.

Population Size and Density

Biologists are interested in **population size (N_t)**: the number of individuals that make up a population at a specified time. They are also interested in **population density (D)**: the number of individuals per unit area or per unit volume of their habitat. Species with a large body size generally have a lower population density than species with a small body size (**Figure 2**). For example, moose (*Alces alces*), a large herbivore that may weigh as much as 700 kg, may have a home range between 5 and 40 km^2. In comparison, a snowshoe hare (*Lepus americanus*), a small herbivore that may weigh up to 2 kg, may have a home range of just 0.1 km^2. Thus, a single moose can use the same amount of habitat as more than 400 snowshoe hares. Large animals require more space than smaller animals because of their body size and food requirements.

population size (N_t) the number of individuals of a specific species that occupies a given area or volume at a given time

population density (D) the number of individuals of the same species that occurs per unit area or volume

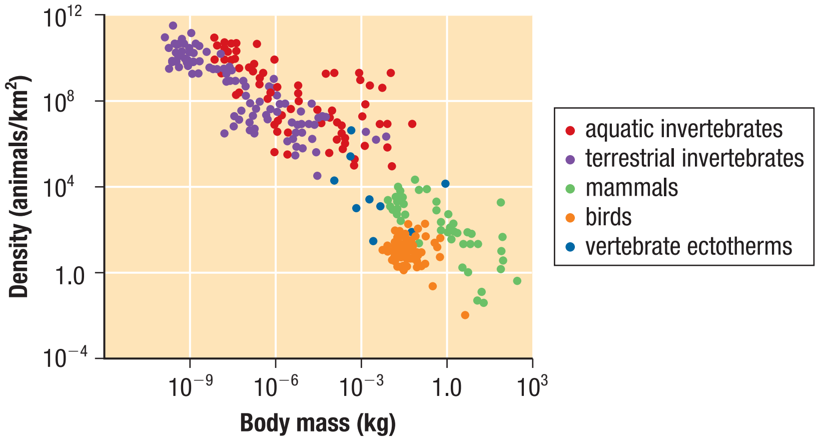


Figure 2 As the body size of animals increases, the number of animals per unit area tends to decrease.

The measure of population density can be misleading because of the unused or unusable space within a habitat. Therefore, ecologists differentiate between the number of individuals within an entire habitat (the **crude density**) and the number of individuals per unit area that is actually used (the **ecological density**).

crude density population density measured in terms of the number of organisms of the same species within the total area of the entire habitat

ecological density population density measured in terms of the number of individuals of the same species per unit area or volume that is actually used by the individuals

Although population size and density are related measures, knowing the density of a population provides more information about the population's relationship to the resources it uses. Population density is calculated by dividing the total number of individuals in the population (N) by the space occupied by the population (S):

$$D = \frac{N}{S}$$

For example, researchers identified 860 mature sugar maple trees (*Acer saccharum*) growing in a 4 ha (hectare) forested area of central Ontario. The density of the trees can be calculated as follows:

$$\frac{860 \text{ trees}}{4 \text{ ha}} = 215 \text{ trees/ha}$$

In the same study, the researchers estimated that there were 75 000 maple seedlings in a 0.5 ha plot. The density of the seedlings is

$$\frac{75\ 000 \text{ seedlings}}{0.5 \text{ ha}} = 150\ 000 \text{ seedlings/ha}$$

A hectare is an area of 10 000 m^2, so this value represents an average density of 15 seedlings per square metre. Clearly, the population of mature trees is less dense than the population of seedlings. However, as the seedlings grow and compete with each other and other species for nutrients, their density will more closely mirror the density of the mature trees.

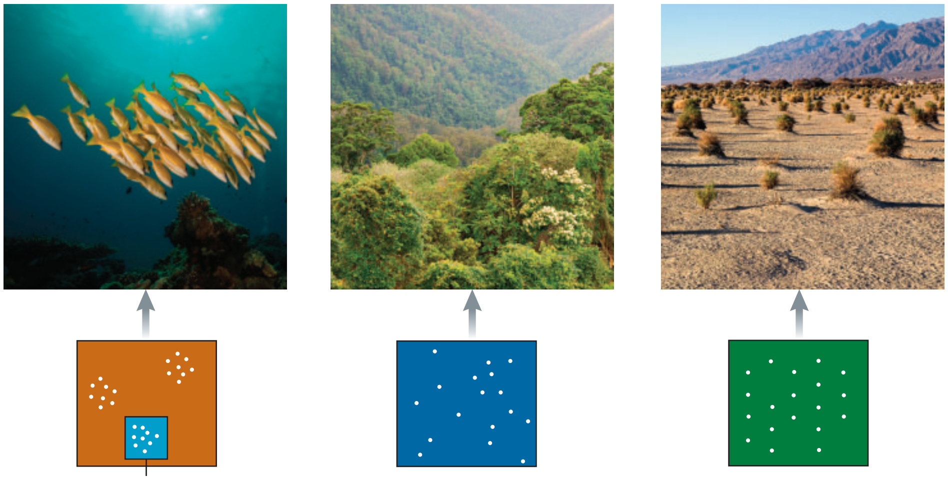
In addition to measuring the population densities of the mature sugar maples and seedlings, the researchers also gathered data on red oak and beech trees in the same area. By comparing the densities of different species over many years, the researchers were able to document changes in the makeup of the entire ecosystem.

Dispersion of Populations

dispersion the pattern of distribution in which a population exists; may be clumped, random, or uniform

Populations can vary in their population **dispersion**, which is the spatial distribution of individuals within a geographic range. Ecologists define three theoretical patterns of dispersion: clumped, random, and uniform (**Figure 3**). Clumped dispersion is a pattern in which individuals in a population are more concentrated in certain parts of the habitat. It is a common pattern and occurs in three situations:

- Suitable living conditions are often distributed in patches. Cattails demonstrate clumped dispersion because they are only able to grow in wet conditions, on the edge of a lake or pond, or in wet soil.
- Populations of some social animals are clumped because mates are easy to locate within groups. The animals may cooperate in rearing offspring, finding food, and defending themselves from predators.
- Populations can be clumped due to limited seed dispersal or asexual reproduction. For example, some species reproduce by asexual clones that remain attached to the parents. Aspen trees exhibit clumped dispersion when they originate asexually from a single plant. Clumping may also occur in species in which seeds, eggs, or larvae lack dispersal mechanisms, such as the ability to move on their own, travel in wind, or float on water. Therefore, offspring grow and settle near their parents, forming clumps.



(a) clumped

A clumped dispersion pattern is one in which individuals are grouped more closely to each other than if they were randomly dispersed.

(b) random

A random dispersion pattern is one in which organisms are distributed independently of each other.

(c) uniform

A uniform dispersion pattern is one in which individuals are more widely separated from each other than they are if they were randomly dispersed.

Figure 3 (a) A clumped pattern of dispersion is evident in fish that live in social groups. (b) A random pattern of dispersion, seen here in an Australian rainforest, is rare in nature. This pattern serves as a yardstick for evaluating other dispersion patterns. (c) A nearly uniform pattern is demonstrated by creosote bushes (*Larrea tridentata*) near Death Valley, California.

Random dispersion occurs when environmental conditions do not vary greatly within a habitat and individuals are neither attracted to nor repelled by others of their species. In random dispersion, individuals are distributed unpredictably, and ecologists use statistics to determine when the distribution of a population is random. Some spiders, burrowing clams, and rainforest trees exhibit random dispersion.

In contrast, individuals can be equally spaced throughout a habitat. This is called uniform dispersion, and it may occur when individuals compete for food, breeding, or nesting grounds. Creosote bushes are uniformly distributed in the dry scrub deserts of the southwestern United States. Mature bushes deplete the surrounding soil of water and secrete toxic chemicals, making it impossible for seedlings to grow. Territorial behaviour, the defence of an area and its resources, can also produce uniform dispersion in some species of animals, such as in colonies of nesting birds.

Whether the spatial dispersion of a population is clumped, random, or uniform depends partly on the size of the organisms and the size of the study area being examined. Oak seedlings may be randomly dispersed on a spatial scale of a few square metres. However, over an entire mixed hardwood forest that covers many hectares, they are clumped under the parent trees. Therefore, dispersion of a population depends partly on the researcher's scale of observation. CAREER LINK

The dispersion of an animal population often varies through time in response to natural environmental changes. Few habitats provide a constant supply of resources, such as food, throughout the year. Many animals move from one habitat to another on a seasonal cycle, based on the distribution of resources. Tropical birds and mammals are often widely dispersed in deciduous forests during the wet season, when food is widely available. During the dry season, these species crowd into narrow "gallery forests" along watercourses, where evergreen trees provide food and shelter.

Studying Populations

Biologists measure population size and density to understand more about population dynamics and to monitor and manage populations of endangered species, economically important species, and agricultural pests. For species of large animals, a simple count of the number of individuals can provide accurate information. For example, ecologists survey the size and density of populations of large African animals (such as lions, wildebeest, and elephants) by aerial counting (flying over in an airplane) (**Figure 4(a)**). This can be difficult, however, if the animals are camouflaged or concealed by trees (**Figure 4(b)**).

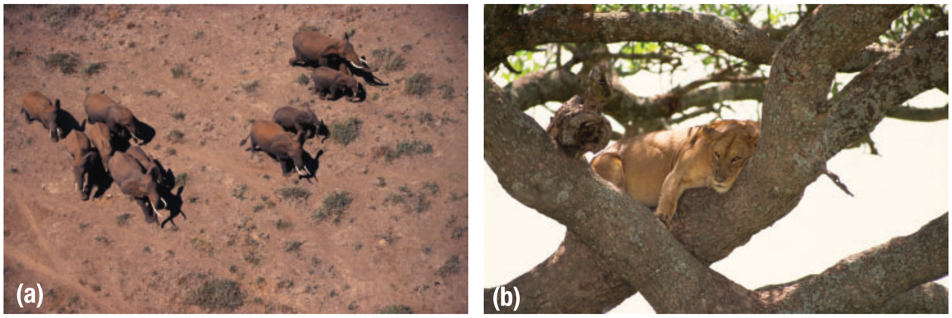


Figure 4 (a) Ecologists study populations of large African animals, such as elephants, using aerial counting. (b) However, counting animals from the air can be difficult if they spend their time under or in trees.

Often, the characteristics of a population make an accurate count impossible. Many populations are dynamic, and their number and geographic location can change over time. For these populations, scientists use sample data and their own observations to estimate population size and density. For other populations, an estimate of size can be made with indirect indicators, such as tracks, nests, or fecal droppings. However, when accurate estimates of population size are important, or when biologists are faced with the challenge of populations that are mobile within their habitat or not readily observable, such as populations of aquatic organisms, ecological sampling methods are used. CAREER LINK

Sampling Populations

quadrat a sampling frame that is used for estimating population size; the frame can be real or virtual

Population size and density are important population characteristics, but they are often difficult to measure accurately. Many sampling techniques have been designed for measuring populations. Each technique has its own strengths and weaknesses, depending on the type of population that is sampled. A common and effective sampling technique for estimating population size and density of small or immobile organisms is **quadrat** sampling.

A quadrat is a square made of wood, plastic, or metal that is used to isolate a sample (**Figure 5**). The size of the quadrat depends on the size of the population being sampled. For example, if a researcher wanted to estimate the population size of dandelions growing in a meadow, the quadrat would likely be 1 m^2. However, if the individuals in the population were much larger, the size of the quadrat would increase.

Figure 5 Quadrats are used to sample populations.

Quadrats must be placed randomly in the area being sampled to avoid bias. They must also be representative of the entire area in question. If a biologist who was determining the density and size of plants in a schoolyard placed quadrats only along a path, for example, the samples would not be random and therefore not representative of the entire population. Bias such as this can be avoided if the quadrats are placed at randomly chosen coordinates. In the tutorial below, you will practise using quadrats to estimate population density.

Tutorial 1 Estimating Population Density

Quadrat sampling is one of the most convenient techniques for measuring the abundance of organisms in a specific area.

Sample Problem 1: Using Quadrats to Estimate Density

A biologist wants to estimate the population size and density of snails on a beach. The beach measures 100 m by 50 m. The biologist randomly places four 1.0 m by 1.0 m quadrats on the beach. Estimate the population size and density if the biologist counts 55, 13, 42, and 35 snails in the four quadrats.

Solution

You can estimate the population density of the snail by calculating the average density of the sampled quadrats.

$$\begin{aligned}\text{estimated population density} &= \frac{\text{total number of individuals}}{\text{sampling area}} \\ &= \frac{55 + 13 + 42 + 35}{(1.0\ \text{m}^2) + (1.0\ \text{m}^2) + (1.0\ \text{m}^2) + (1.0\ \text{m}^2)} \\ &= 36.2\ \text{snails/m}^2\end{aligned}$$

Assuming that the sample is representative of the total study area, the estimated population density of the snails is 36.2 snails/m^2.

You can estimate the population size by multiplying the estimated population density by the total study area.

$$\begin{aligned}\text{estimated population size} &= (\text{estimated population density})\ (\text{total size of study area}) \\ &= (36.2\ \text{snails/m}^2)(5000\ \text{m}^2) \\ &= 181\ 000\ \text{snails}\end{aligned}$$

Practice

1. In a study of eastern red-backed salamanders (*Plethodon cinereus*), a biologist randomly placed seven 1.0 m by 1.0 m quadrats in a field that measured 100 m by 100 m. Estimate the population density and size if the biologist found 0, 1, 1, 2, 0, 1, and 3 salamanders in the seven quadrats. [ans: 1.1/m^2, 11 000]
2. In a survey of northern mountain ash seedlings in northern Ontario, researchers randomly placed eight 1.0 m by 2.0 m quadrats in a field that measured 100 m by 150 m. Estimate the population density and size if the researchers found 2, 0, 0, 8, 6, 1, 1, and 3 seedlings in the eight quadrats. [ans: 1.3/m^2, 20 000]

MARK-RECAPTURE SAMPLING

Some animal species continually move around, seeking protection, food, and shelter in hard-to-see areas. These species are difficult, if not impossible, to count. One common sampling technique that is used to estimate the population size of these species is the **mark-recapture method**. A specific number of animals in the natural population is captured, marked, or tagged in some way and then released back to the population. After a period of time, when the marked animals have mixed with the unmarked animals, another sample is captured. Biologists use the proportion of marked to unmarked animals in the second sample to estimate the size of the entire population.

mark-recapture method a sampling technique for estimating population size and density by comparing the proportion of marked and unmarked animals that are captured in a given area; sometimes called the capture-recapture method

The accuracy of this method is dependent on five assumptions:

- The chances for each individual in the population to be caught are equal and constant for both the initial capture and the recapture. Marked individuals must not be or become easier or more difficult to catch.
- The proportion of marked to unmarked animals remains the same between captures. No new individuals can enter the population through birth or immigration, and no individuals can leave through death or emigration.
- Enough time is allowed between the initial capture and subsequent recapture for all the marked individuals to disperse randomly throughout the population.
- The captured animals are not adversely affected by their marks.
- The marked animals do not lose their marks.

Based on these assumptions, the estimated population size can be calculated as follows:

$$\frac{\text{total number marked } (M)}{\text{total population } (N)} = \frac{\text{number of recaptures } (m)}{\text{size of second sample } (n)}$$

or

$$N = \frac{Mn}{m}$$

where

N = estimate of the total population size
M = total number of animals captured, marked, and released on the first visit
n = total number of animals captured on the second visit
m = number of marked animals that were recaptured on the second visit

In the following tutorial, you will estimate population sizes based on data from mark-recapture sampling.

Tutorial 2 Estimating Population Size

The mark-recapture sampling method is used to measure the population size of large or highly mobile animals.

Sample Problem 1: Mark-Recapture Sampling

Biologists were studying a saw-whet owl population of unknown size. They captured, banded, and released 30 individuals. They waited until they assumed that the released individuals had moved randomly through the population. Then they captured a second sample of 80 individuals and found that 12 individuals were marked. Use these values to estimate the population size.

We can assume that the ratio of marked individuals to the size of the total population equals the ratio of marked individuals recaptured in the second sample.

$$N = \frac{Mn}{m}$$

$$N = \frac{30 \times 80}{12}$$

$$N = 200$$

Therefore, the estimated population size is 200.

Practice

1. Biologists captured 75 red foxes in a forested area and marked them with ear tags. Exactly 10 days later, they recaptured 45 red foxes and found that 15 had ear tags. Estimate the red fox population in this area. [ans: 225 red foxes]
2. In a northern Ontario lake, 208 lake trout were captured and marked with a tag on one fin. Two weeks later, 185 lake trout were recaptured and 13 had tags. Estimate the lake trout population in this lake during the study period. [ans: 2960 lake trout]
3. Imagine that you capture a sample of 180 butterflies in a park, mark them, and then release them. A week later, you recapture 210 butterflies and find that 30 are marked. Determine the estimated butterfly population in the park during the study period. [ans: 1260 butterflies]

Tracking Populations

Tracking animals provides useful information about their behaviour. Animals can be tracked with special transmitters using Global Positioning System (GPS) technology and satellites. They can also be tracked with DNA sampling, by collecting and testing their droppings and other biological materials. Biologists have been able to learn a great deal about the range, distribution, and population density of various species with these techniques. For example, satellite tracking of 25 female sea turtles showed that their migrations followed three major routes from Gabon in Africa (**Figure 6**). This research was vital for determining which conservation strategies should be used for the sea turtles. WEB LINK

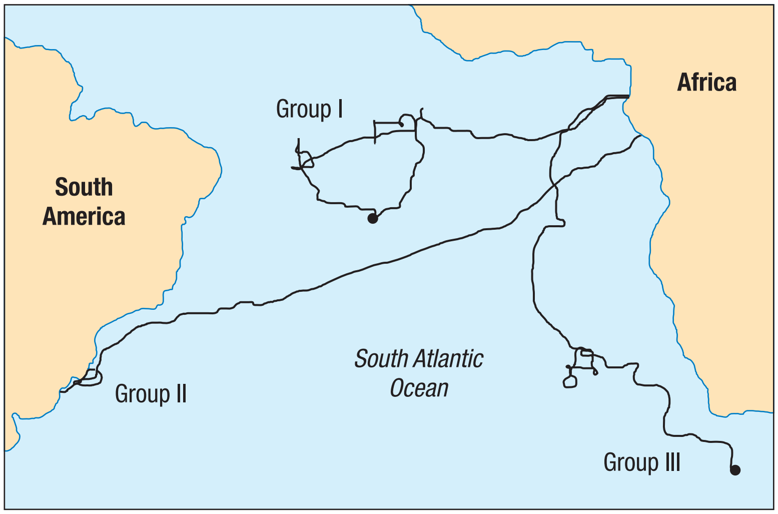


Figure 6 Satellite tracking of sea turtle migrations off the western coast of Africa

Another study, called the Y2Y project (for "Yukon to Yellowstone"), started with a female wolf nicknamed "Pluie" (after the French word for "rain"). She was collared by researchers in June of 1991 in Alberta's Peter Lougheed Provincial Park and tracked for two years. Satellite locations recorded Pluie's travels. In a nine-month period, she wandered over 103 000 km^2, an area 15 times as large as Banff National Park, and she spent time with five different wolf packs. In her travels, she passed through three states, two provinces, private lands, and First Nations, Inuit, and Métis lands (**Figure 7**).

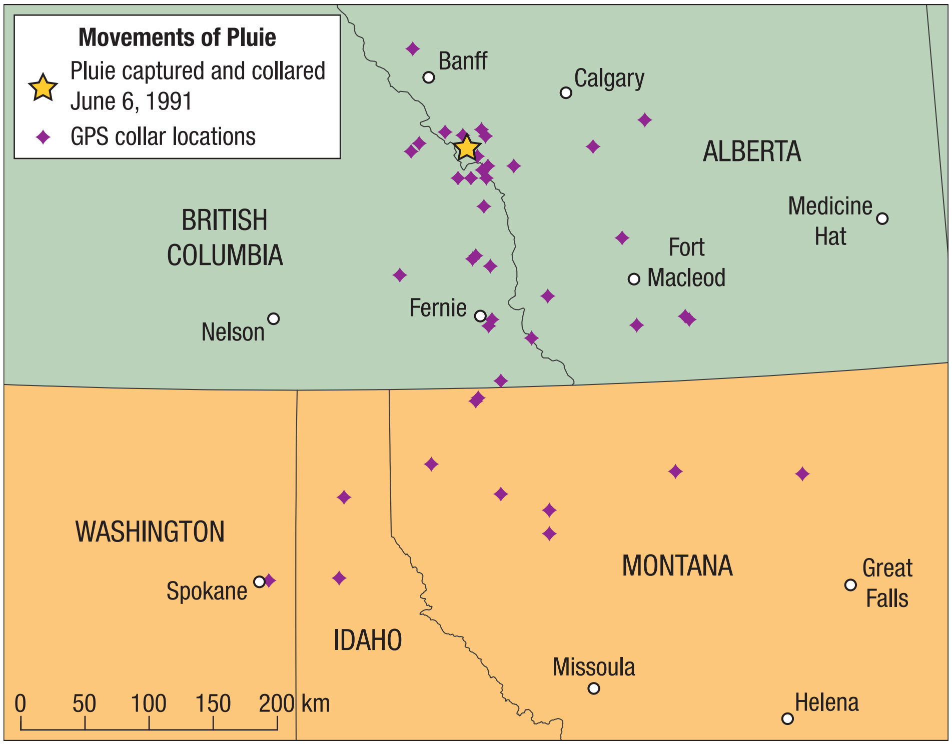


Figure 7 Pluie travelled through Banff National Park into southwest British Columbia, then into Montana, Idaho, and Washington state before returning to British Columbia.

The Ethics of Studying Populations

Marking and tracking can be excellent techniques for monitoring and sampling a population. However, there is an ethical debate about their potential impact on the animals involved. Some scientists have expressed concern that the handling of animals during data collection for population density and size may alter their behaviour after their release or reduce their reproductive ability. Other scientists are concerned that trapping methods may be harmful. The long-term effects of repeated tranquilizing of large animals are not known, nor are the effects of collars and tags. The effects of pursuing, capturing, and marking animals are also not known. However, a recently published 10-year study of banded King penguins by French researchers has shown that banding the penguins on a flipper has reduced their lifespan and their reproductive fitness.

The Canadian Council on Animal Care (CCAC) is in the process of developing a set of guidelines for ethical wildlife research. The CCAC is encouraging researchers to reduce their use of animals in studies as much as possible, to support and develop techniques that will minimize pain and distress in animals, and to replace trapping with computer estimations wherever possible.

Measuring and estimating population size are necessary for developing population management strategies and reducing the effects of environmental stressors, whether natural or human-made. However, efforts should be made to ensure that the use of animals in research is valid, humane, justifiable, and considerate.

12.1 Review

Summary

- Biologists use measurements, such as population size and population density, to describe and monitor populations. These measurements also help biologists manage species.
- Populations in a given geographical range show one of three dispersion patterns: clumped, uniform, or random.
- Biologists use quadrat sampling and mark-recapture sampling to estimate population size and density.
- Satellite and other technology can be used to track animals that migrate or move over long distances.
- Ethical issues and concerns need to be considered when studying and monitoring wildlife populations.

Questions

1. (a) What are the three types of dispersion?
   (b) Do dispersion patterns of populations always stay the same? Why or why not? K/U
2. Use the Internet to find satellite tracking data for a species of wildlife, and answer the following questions. Be sure to include the URL of the site you used to answer the questions. 🌐 T/I A
   (a) What animals are being tracked?
   (b) How far did the animals travel?
   (c) Where were they located?
   (d) How are the data being used by scientists?
   (e) How can such data help to protect endangered species?
3. Using a Venn diagram or t-chart, compare and contrast quadrat sampling and mark-recapture sampling for estimating population size. What underlying assumptions must be made for each technique to be effective? K/U C
4. Research the invasive plant species called garlic mustard (*Alliaria petiolata*) and the impact it is having in Ontario. 🌐 T/I
   (a) When and how was garlic mustard introduced into North America?
   (b) Identify the major problem(s) it causes for native species.
   (c) What, if anything, is being done to stop its spread?
5. Researchers captured 18 black bears in a large forested area. They marked and released the bears. In a second trial, they captured 16 black bears and found that 5 had been marked. Estimate the overall population of black bears in this area. T/I
6. To estimate the size of a dandelion population in a schoolyard, a biology student randomly placed five 1.0 m by 1.0 m quadrats in a site that measured 40.0 m by 40.0 m. The numbers of dandelions in the quadrats were 6, 10, 2, 4, and 7. K/U T/I
   (a) Estimate the density and size of the dandelion population in this study site.
   (b) What assumptions did the student have to make when estimating the density and size of the population?
7. A biologist wanted to estimate the density and size of a burrowing prairie dog population in a grassland habitat. The biologist had to choose between quadrat sampling and mark-recapture sampling. T/I A
   (a) Which sampling technique do you think would be easier to implement, and why?
   (b) Which sampling technique do you think would be more effective, and why?
8. A team of wildlife researchers plans to study caribou that live in the Arctic tundra using mark-recapture sampling. T/I
   (a) What challenges might the researchers experience when estimating the density and size of the caribou population? Is there a better sampling technique that could be used for this population?
   (b) What are the possible potential short-term and long-term effects of studying the caribou population?

🌐 WEB LINK

Demography

12.2

Populations are dynamic. Depending on the species and the environmental conditions, population numbers can undergo hourly, daily, seasonal, or annual changes. **Demography** is the study of these changes. Specifically, it is the statistical study of the processes that change the size and density of a population through time. Ecologists use demographic analysis to predict the growth of a population. The birth rate (**natality**), death rate (**mortality**), movement of individuals into a population (**immigration**), and movement of individuals out of the population (**emigration**) can be used to determine the growth rate of the population in a given period of time. Ecologists follow these demographic changes in populations through routine sampling.

Demographic data can also be used by conservation ecologists to develop plans to protect endangered species. For example, demographic data for northern spotted owls (*Strix occidentalis caurina*) helped to convince the courts to restrict logging in the owl's primary habitat, the old growth forests of the Pacific Northwest (**Figure 1**). To analyze and show demographic data about wildlife, ecologists use life tables and survivorship curves.

demography the study of the growth rate, age structure, and other characteristics of populations

natality the birth rate in a population

mortality the death rate in a population

immigration the movement of individuals into a population

emigration the movement of individuals out of a population

Figure 1 Ecologists used demographic data to convince the courts to protect the habitat of the northern spotted owl.

Life Tables

Although every species has a characteristic lifespan, the lifespan of each individual varies. Individuals may die from starvation, disease, predation, or the inability to find a suitable habitat. Life insurance companies developed techniques for measuring human mortality rates, and ecologists have adapted these approaches to study non-human populations.

A **life table** summarizes the demographic characteristics of a population (**Table 1**). To collect life table data for short-lived organisms, demographers usually mark a group of individuals born around the same time (a **cohort**) and then monitor the survival of these individuals until all of them die.

life table a chart that summarizes the demographic characteristics of a population

cohort a group of individuals of similar ages

Table 1 Life Table for a Cohort of 843 Individuals of *Poa annua* (annual bluegrass)

Age interval (in months)	Number alive at start of age interval	Number dying during age interval	Age-specific mortality rate	Age-specific survivorship rate	Proportion of original cohort alive at start of age interval	Age-specific fecundity (seed production)
0–3	843	121	0.144	0.856	1.000	0
4–6	722	195	0.270	0.730	0.856	300
7–9	527	211	0.400	0.600	0.625	620
10–12	316	172	0.544	0.456	0.375	430
13–15	144	90	0.625	0.375	0.171	210
16–18	54	39	0.722	0.278	0.064	60
19–21	15	12	0.800	0.200	0.018	31
22–24	3	3	1.000	0.000	0.004	10
25+	0	–	–	–	–	–

For organisms that live more than a few years, researchers might sample the population for one or two years and record the ages at which individuals die. The researchers could then extrapolate these results over the species' lifespan. In any life table, the lifespans of individuals are divided into age intervals. For species with a short lifespan, days, weeks, or months are used. For longer-living species, years or ranges of years are more useful. CAREER LINK

age-specific mortality the proportion of individuals that were alive at the start of an age interval but died during the age interval

age-specific survivorship the proportion of individuals that were alive at the start of an age interval and survived until the start of the next age interval

The mortality rate is the number of deaths in a population per unit of time. It can be viewed from two different perspectives. **Age-specific mortality** is the proportion of individuals that were alive at the start of an age interval but died during the age interval. It can also be viewed from the perspective of **age-specific survivorship**: the proportion of individuals that were alive at the start of one age interval and were still alive at the start of the next age interval. For the data in Table 1, the age-specific mortality rate and the age-specific survivorship rate during the 4- to 6-month age interval can be calculated as follows:

$$\begin{aligned}\text{age-specific mortality rate} &= \frac{\text{number that died during the interval}}{\text{number alive at the start of the interval}}\\ &= \frac{195}{722}\\ &= 0.270\\ \text{age-specific survivorship} &= \frac{\text{number still alive at the end of the interval}}{\text{number alive at the start of the interval}}\\ &= \frac{722 - 195}{722}\\ &= 0.730\end{aligned}$$

For any age interval, the sum of the age-specific mortality and the age-specific survivorship must equal 1. In the example above, $0.270 + 0.730 = 1$.

A life table also summarizes the proportion of the cohort that survived to a particular age. This statistic identifies the probability that any randomly selected newborn will still be alive at that age. For example, using the data in Table 1, the probability of an individual being alive at the 4- to 6-month age interval can be calculated as follows:

$$\begin{aligned}\text{probability of being alive at a specific age} &= \frac{\text{number alive at the start of the age interval}}{\text{number alive at the start of the initial age interval}}\\ &= \frac{722}{843}\\ &= 0.856\end{aligned}$$

The probability of a randomly selected newborn being alive at the 4- to 6-month age interval is 0.856. Conversely, the probability that the newborn will not be alive at this age interval is 0.144. **Figure 2** shows the relationship between survivorship and age for the annual bluegrass plant, based on the data in Table 1.

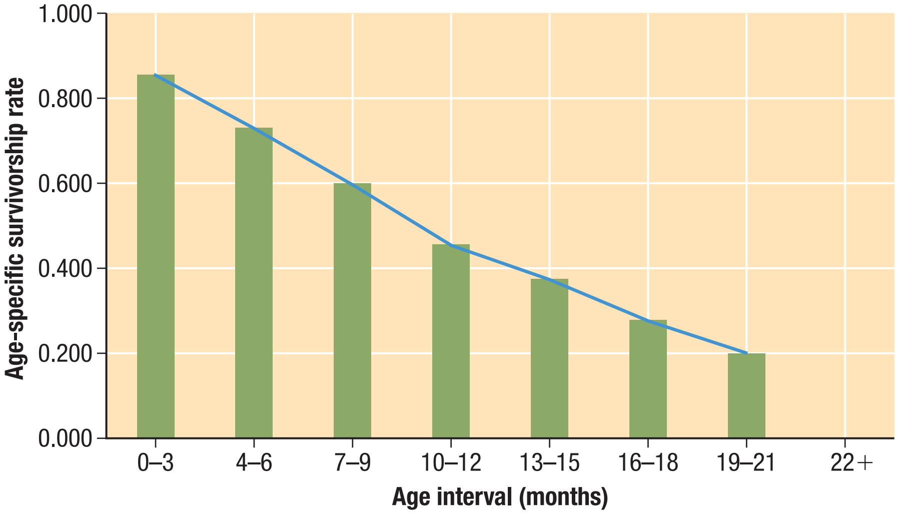
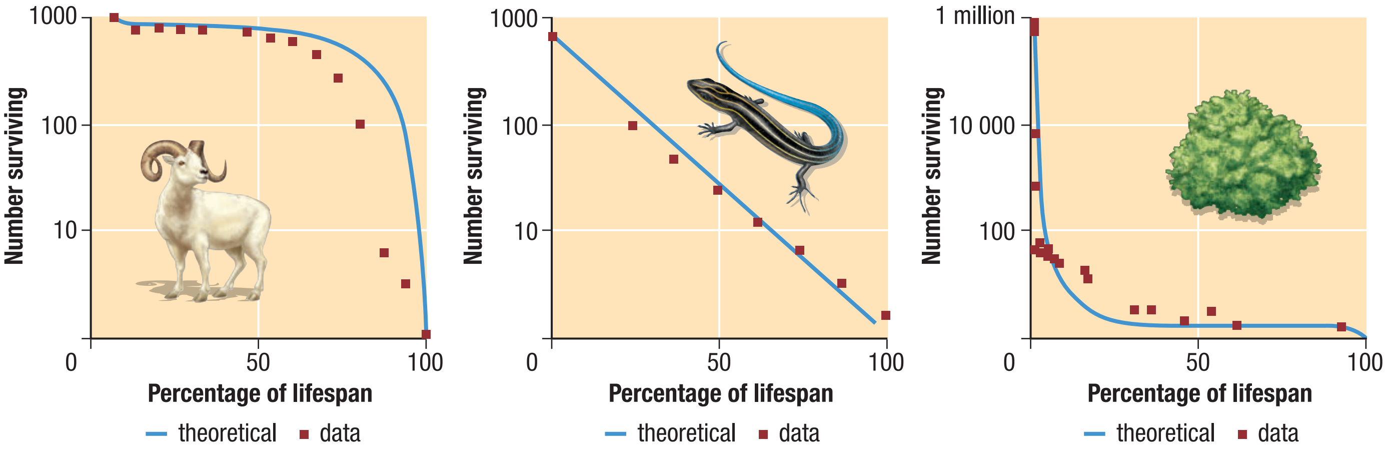


Figure 2 Graph of age-specific survivorship for the annual bluegrass plant by age interval

Survivorship Curves

Ecologists use life tables to help them understand a species' ability to survive hardship. Data about survival can be depicted graphically in a **survivorship curve**, which displays the survival of individuals over the lifespan of the species. Ecologists have identified three general survivorship curves: type I, type II, and type III. Most organisms exhibit survivorship patterns that fall somewhere between these general patterns (**Figure 3**).

survivorship curve a graphic display of the rate of survival of individuals over the lifespan of a species



(a) Type I **(b)** Type II **(c)** Type III

Figure 3 The survivorship curves (red) of many organisms, such as (a) the Dall mountain sheep, (b) the five-lined skink, and (c) the perennial desert shrub, roughly match one of three idealized patterns (blue).

Type I curves are relatively flat at the start, reflecting a low death rate in the early and middle years, and drop steeply as the death rate increases in the older age groups (Figure 3(a)). These curves are typical for large animals that produce few young and provide their young with extended care, which reduces juvenile mortality. For example, Dall mountain sheep (*Ovis dalli*) produce only one or two offspring at a time and nurture them through their vulnerable first year. Beginning around their second year, the offspring are better able to fend for themselves and are at a lower risk for mortality. Species that have type I survivorship curves generally have a long gestation period and newborns that are usually unable to care for themselves. Many species of large animals, such as moose, deer, and humans, have type I curves (**Figure 4(a)**).

Type II curves reflect a relatively constant rate of mortality in all age groups. This pattern produces a steadily declining survivorship (Figure 3(b)). Many lizards, such as the five-lined skink (*Eumeces fascistus*), as well as songbirds and small mammals, face a constant probability of mortality from predation, disease, and starvation at any age and exhibit a type II pattern in their survivorship (**Figure 4(b)**). Organisms that have a type II curve generally have a relatively short gestation period. These organisms often feed on type III organisms but are preyed on by type I organisms.

Figure 4 (a) Deer are examples of organisms with a type I survivorship curve. (b) Five-lined skinks are examples of type II organisms.

Type III curves drop rapidly at the start, reflecting a very high death rate early in life, and then flatten out as the death rate declines for the few individuals that survive the critical stage (Figure 3(c)). The black crappie (*Pomoxis nigromaculatus*), a bony fish that can be found from Manitoba to Mexico, has high juvenile mortality, followed by a period of low mortality once the offspring reach a critical age and size. At spawning time, the female lays up to 150 000 eggs in a shallow depression on the bottom of a lake, in less than 2 m of water. The male fish protects the eggs for about one week, until the young hatch, but then is the first to feed on the young. This type of curve is characteristic of species that produce a large number of offspring. Many plants, insects, marine invertebrates, and fish have a type III survivorship curve.

Survivorship curves give a base line for other population monitoring and act as a reference point for new data. For example, if a population of Dall sheep is monitored and there is a steep decline in the survival of the young sheep, a biologist might conclude that something abnormal, such as an abundance of predators, poaching, overcrowding, or disease, is affecting the population. Conversely, if a biologist observes that a population of black crappies is showing a stunted growth pattern, the biologist would be likely to support a high catch limit on mature fish to promote a healthier overall fish population.

Fecundity

fecundity the potential for a species to produce offspring in a lifetime

Fecundity is the potential reproductive capacity of an individual or population. This varies from species to species. For example, the horseshoe crab (*Limulus polyphemus*) can lay hundreds of thousands of eggs a year (**Figure 5(a)**), while the Asian elephant (*Elephas maximus*) produces an average of only four offspring during a lifetime of approximately 60 years (**Figure 5(b)**). Fecundity in a population can increase or decrease depending on environmental conditions and several other regulating factors.

Figure 5 (a) Horseshoe crabs can lay up to 90 000 eggs in a single spawning season. (b) Asian elephants have the longest gestation period of any animal—almost 22 months!

Fecundity is highly dependent on environmental conditions. In years when there is plenty of food and the climate is optimal, species tend to have higher rates of reproduction. In years when there is little food and precipitation, reproduction rates can drop dramatically.

All populations have an age structure that describes the relative number of individuals in each age category. Individuals can be categorized as younger than the age of sexual maturity (pre-reproductive), reproducing age (reproductive), or older than the maximum age of reproduction (post-reproductive). A population's age structure reflects its recent growth history and predicts its future growth potential. For example, a population that consists of many pre-reproductive individuals has grown in the recent past and will continue to grow as the young individuals mature and reproduce. Another characteristic that influences fecundity and population growth is **generation time**: the time needed to complete one generation. A species with a small body size, such as *E. coli* or *Pseudomonas*, has a very short generation time because the individuals reach maturity very quickly. On the other hand, humans and whales, with a much larger body size and later maturity, have much longer generation times (**Figure 6**).

generation time the average time between the birth of an organism and the birth of its offspring

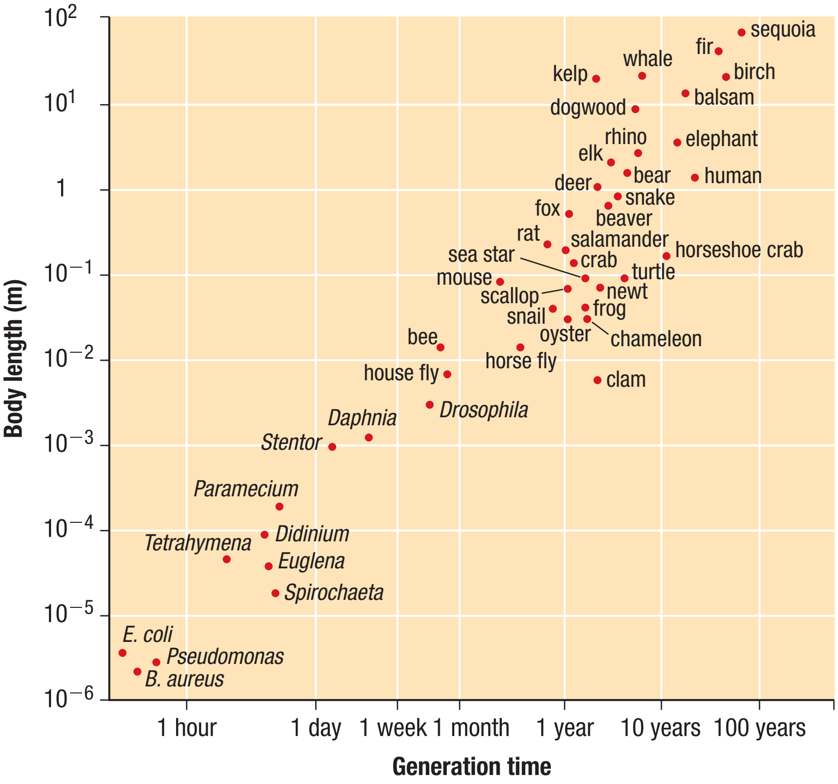


Figure 6 Generation time increases with body size among bacteria, protists, plants, and animals. The logarithmic scale on both axes compresses the data into a straight line.

Populations of sexually reproducing organisms also vary in their **sex ratio**: the relative proportion of males and females. In general, the number of females in a population has a bigger impact on population growth than the number of males because only females produce offspring. Moreover, in many species, one male can mate with several females, so the number of males may have little effect on the population's reproductive output. In northern elephant seals, for example, mature bulls fight for dominance on the beaches where the seals mate. Only a few males may ultimately inseminate 100 or more females. Thus, the presence of other males in the group may have little effect on the size of future generations. On the other hand, in animals that form lifelong pair bonds, such as geese and swans, the numbers of both males and females influence reproduction in the population.

sex ratio the relative proportion of males and females in a population

Life tables include data for age-specific fecundity, which is the average number of offspring produced by surviving females during each age interval. Table 1 (page 593) shows that each plant in the 3- to 6-month age interval produced an average of 300 seeds. In some species, including humans, fecundity is highest in individuals of intermediate age. Younger individuals have not yet reached sexual maturity, and older individuals are past their reproductive prime. However, fecundity increases steadily with age in some plants and animals.

Population ecologists are interested in the proportion of reproducing individuals in a population. This information is particularly relevant to the conservation of species in which individuals are rare or widely dispersed across their habitat.

High Fecundity versus Extensive Parental Care

An animal that has many offspring (or has high fecundity) normally does little to care for them. For example, a female wild coho salmon (*Oncorhynchus kisutch*) produces 2400 to 4500 eggs and then dies before the eggs hatch. A hawksbill turtle (*Eretmochelys imbricata*) may lay as many as 100 eggs in a nest in the sand, immediately leaving the offspring to hatch and fend for themselves (**Figure 7(a)**). It is estimated that only 1 in 1000 hatchings reach adulthood.

In contrast, animals that have just one or two offspring per year tend to be very protective of their offspring. For example, black bears (*Ursus americanus*) stay with their cubs for approximately two years (**Figure 7(b)**). They give birth to their cubs during the late winter, while hibernating in their den. A mother usually gives birth to one or two cubs, although she may have as many as three in a very fertile year when there is a lot of food. The mother spends the following year and a half weaning, feeding, and teaching her cubs what to eat and how to survive. She does not breed that year, and the cubs spend their first winter in the den with her.

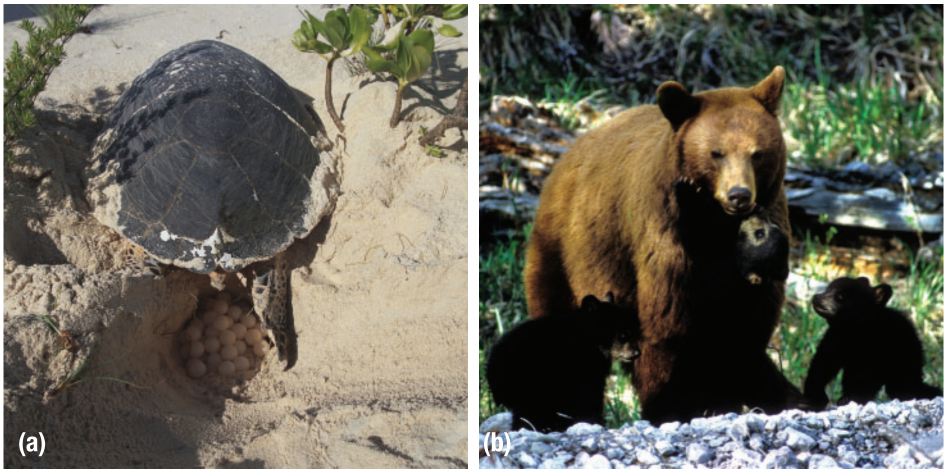


Figure 7 (a) Mature female hawksbill turtles lay several large batches of eggs. (b) The mother black bear stays with her cub through its entire first year and a half of life.

Changes in Population Size

As you have seen in this section, populations can increase or decrease according to environmental conditions and several regulating factors. To monitor and evaluate population dynamics, ecologists must be able to quantify these changes. Natality, mortality, immigration, and emigration numbers can be used to determine the change in the size of a population in a given time period. The population change of any population can be calculated mathematically using the following formula:

$$\text{population change} = (\text{births} + \text{immigration}) - (\text{deaths} + \text{emigration})$$

Ultimately, population size is determined by changes in the number of individuals that immigrate, emigrate, are born, and die. If natality and immigration are equal to mortality and emigration, then a population's size will remain stable. However, when natality and immigration exceed mortality and emigration, there is population growth. When mortality and emigration are greater than natality and immigration, however, population size will decrease. Both biotic and abiotic factors can affect the rates of natality, mortality, immigration, and emigration. In the next section, you will examine models that are used to describe the patterns of population growth.

UNIT TASK **BOOKMARK**

You can use what you have learned about demography when you are analyzing the effect of an abiotic or biotic factor on human population growth in the Unit Task on page 688.

12.2 Review

Summary

- Populations are dynamic and change based on many factors, including birth and death rates, immigration, emigration, fecundity, and generation time.
- Life tables are used to describe and understand the population dynamics of a species.
- Survivorship curves depict survival in a population at different ages and can be constructed for a given cohort based on the data in a life table.
- There is an inverse relationship between fecundity and parental care. In general, the higher the fecundity of a species, the lower the parental care is.

Questions

1. List the four factors that change the number of individuals in a population, and describe how each factor affects the population. K/U
2. (a) What is the mathematical relationship between age-specific mortality and age-specific survivorship?
   (b) If the age-specific mortality of a population is 0.297, what is the age-specific survivorship? K/U
3. How does a life table help us understand the demography of a population? K/U T/I
4. Choose an organism that has each type of survivorship curve, and explain why it has this type of curve. K/U T/I
5. Some organisms, such as ants and bees, depend on social structure and behaviour to enhance their survival. Using the Internet or other sources, find out how the social structure of an ant hill or a bee colony contributes to the survival of the population. T/I
6. Use Table 1 on page 593 to answer the following questions about the cohort of 843 individuals in the annual bluegrass population. T/I
   (a) At which age interval is the population reproducing at the highest rate?
   (b) At which age interval is the mortality rate at its highest?
   (c) What is the probability of a member of the cohort being alive in the 13- to 15-month age interval?
   (d) Based on the information in Table 1, which type of survivorship curve would best reflect this population?
7. List and describe three factors that could affect fecundity in a population. K/U
8. A population of mice started with 90 individuals. Over a given time interval, there were 340 births and 45 deaths. As well, 65 individuals immigrated. There was no emigration. Calculate the population change. T/I
9. Once endangered species, both the peregrine falcon and the Aleutian Canada goose have made a comeback from the brink of extinction (**Figure 8**). Choose a mammal, bird, or fish from the list of endangered species in Canada. Use the Internet to find the primary cause of this species' decline. What lessons can be learned that could prevent the decline of similar species in the future? Share your findings with your classmates. T/I C

Figure 8 The Aleutian Canada goose was listed as an endangered species in the U.S. in 1973 but was removed from the list in 2001.

WEB LINK

12.3 Changes in Population Size over Time: Modelling Population Growth

Figure 1 Mosquitoes are an important link in food chains, but they can sometimes carry diseases.

population dynamics the change in a population over time

Most Canadians consider mosquitoes to be pests, and some would prefer to see them eradicated (**Figure 1**). Mosquitoes bite, and they can ruin outdoor activities. In addition, mosquitoes are vectors for diseases, making them a public health concern as well as a nuisance. However, mosquitoes help ecosystems maintain balance. They are an essential food source for many birds, bats, young fish, spiders, and other insects. Removing mosquitoes from an ecosystem would remove a link from the bottom of the food chain, potentially causing it to collapse.

Each mosquito population has its own habitat. When this habitat changes, whether through natural or human intervention, so does the mosquito population. The Public Health Agency of Canada, along with provincial and local government agencies, monitor mosquito populations for the spread of diseases such as the West Nile virus. Entomologists (scientists who study insects) use models of mosquito population growth along with weather patterns to determine when there is the potential for large larval populations. While models are not always accurate, when large mosquito populations are anticipated, local municipalities can alter the environment, often through cleanup, to prevent them from hatching. CAREER LINK

As you learned in Section 12.2, animal populations change over time due to births, deaths, and the immigration and emigration of individuals between different populations. These changes, or **population dynamics**, are affected by environmental conditions and other regulating factors. Depending on the species and environmental conditions, populations can change hourly, daily, seasonally, and annually. Because of the many factors involved, population changes can be unpredictable. However, being able to predict or understand how and why the size of a population changes over time can be very useful for species management. CAREER LINK

Exponential Model of Population Growth

While being able to calculate the basic population change is helpful (Section 12.2), ecologists are particularly interested in the population growth rate: the fractional rate at which the number of individuals in a population increases or decreases. The population growth rate refers to the change in a population over a unit time period and is usually expressed as a percentage of the number of individuals in the population at the beginning of this period. The growth rate of a population can be calculated as follows:

$$\text{population growth rate} = \frac{(\text{births} + \text{immigration}) - (\text{deaths} + \text{emigration})}{\text{initial population}} \times 100$$

A positive growth rate indicates that the population is increasing, while a negative growth rate indicates that the population is decreasing. A growth rate of zero indicates that there was no change in the population size; in other words, the net difference between births, deaths, and migration is zero.

exponential model of population growth a pattern of population growth in which organisms reproduce continuously at a constant rate

Some species reproduce continuously, with no specific breeding season. The sizes of these populations have the potential to increase exponentially, by a constant ratio per unit of time. Populations of bacteria are the most obvious example, but some multicellular organisms also exhibit this **exponential model of population growth**.

Bacteria reproduce by binary fission. A parent cell divides in half, producing two daughter cells. Each daughter cell divides to produce two granddaughter cells. The generation time in a bacterial population is the time between successive cell divisions. If no bacteria in the population die, the population doubles in size each generation.

Bacterial populations grow quickly with an ideal temperature and unlimited space and food. For example, the generation time for a population of the human intestinal bacterium *E. coli* can be as short as 20 min. A population of one bacterium doubles to two cells after one generation, to four cells after two generations, and to eight cells after three generations (**Figure 2**). After only 8 h (24 generations), the population size is more than 16 million. If such growth could be sustained, after a single day (72 generations), the population would theoretically number nearly 5×10^{21} cells. This is an example of exponential growth.

Populations of large multicellular organisms, such as humans, also have the potential for exponential growth. Over a given time period, if we temporarily ignore emigration and immigration, the following relationship will hold:

change in population size = number of births − number of deaths

In mathematics, the symbol *d* is used to indicate "incremental change" or "change in." *N* is the population size, so *dN* is the change in population size and *dt* is the change in time. *B* is the number of births and *D* is the number of deaths during the time period. Thus, $\frac{dN}{dt}$ symbolizes the change in population size over time.

$$\frac{dN}{dt} = B - D$$

This equation can be used for any population if we know the exact numbers of births and deaths. Ecologists usually express difference between births and deaths as a **per capita growth rate (*r*)**. This allows them to apply the model to a population of any size. The per capita birth rate (*b*) is the number of births in the population during the specified time period divided by the population size:

$$b = \frac{B}{N}$$

Similarly, the per capita death rate (*d*) is the number of deaths divided by the population size:

$$d = \frac{D}{N}$$

For example, in a population of 2000 field mice, if 1000 mice are born and 200 mice die during one month, the per capita birth rate of the mice would be 0.5 individuals per month. The death rate would be 0.1 individuals per month.

$$b = \frac{1000}{2000}$$

$$= 0.5 \text{ births per individual per month}$$

$$d = \frac{200}{2000}$$

$$= 0.1 \text{ deaths per individual per month}$$

Of course, no mouse can give birth to half an offspring or die one-tenth of a death. However, these rates tell us the births and deaths averaged over all mice in the population. Per capita birth and death rates are always expressed over a specified time period. For organisms with a long lifespan, such as humans, the time is measured in years. For organisms with a short lifespan, such as fruit flies, the time is measured in days. We can calculate per capita birth and death rates from data in a life table.

The population growth equation can now be revised to use per capita birth and death rates instead of the actual numbers of births and deaths. The change in the size of a population during a given time period $\left(\frac{dN}{dt}\right)$ depends on the per capita birth and death rates, as well as the number of individuals in the population. Mathematically, we can write the relationship as follows:

$$\begin{aligned}\frac{dN}{dt} &= B - D \\ &= bN - dN \\ &= (b - d)N\end{aligned}$$

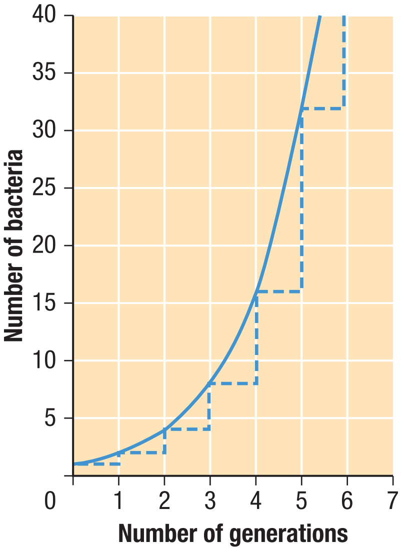


Figure 2 Bacterial population growth

per capita growth rate (*r*) the difference between the per capita birth rate and the per capita death rate of a population

This equation describes the exponential growth of a population. (Note that, in calculus, $\frac{dN}{dt}$ is the notation for the population growth rate. The d in $\frac{dN}{dt}$ is not the same d that we use to symbolize the per capita death rate. The d in this equation stands for "change in.")

The difference between the per capita birth rate and the per capita death rate, $b - d$, is the per capita growth rate of the population, r. Like b and d, r is always expressed per individual per unit of time. Using the per capita growth rate, r, in place of $(b - d)$, the exponential growth rate can be written as follows:

$$\frac{dN}{dt} = rN$$

If the birth rate exceeds the death rate, r has a positive value ($r > 0$) and the population is growing. In the field mice example, r is $0.5 - 0.1 = 0.4$ mice per mouse per month. If, on the other hand, the birth rate is lower than the death rate, r has a negative value ($r < 0$) and the population size is shrinking. If the birth rate equals the death rate, r is zero and the population size is not changing. This situation is known as **zero population growth (ZPG)**. Even under ZPG, births and deaths still occur, but the number of births is approximately equal to the number of deaths.

zero population growth (ZPG) a situation in which the death rate and the birth rate are in equilibrium

A population will grow as long as the per capita growth rate is positive ($r > 0$). For the hypothetical population of field mice, we started with $N = 2000$ mice and calculated a per capita growth rate of 0.4 mice per individual per month. In the first month, the population grew by $0.4 \times 2000 = 800$ mice (**Figure 3**). At the start of the second month, $N = 2800$ and $r = 0.4$ (no change). Thus, in the second month, the population will grow by $0.4 \times 2800 = 1120$ mice. Notice that the population growth increases each month, even though r remains constant, because more individuals are reproducing. In less than two years, the mouse population will increase to more than one million! A graph of exponential population growth has a characteristic J shape, getting steeper through time. The population grows at an ever-increasing pace because the change in the population size depends on the number of individuals in the population and the per capita growth rate.

Month	Old population size		Net monthly increase		New population size
1	2 000	+	800	=	2 800
2	2 800	+	1 120	=	3 920
3	3 920	+	1 568	=	5 488
4	5 488	+	2 195	=	7 683
5	7 683	+	3 073	=	10 756
6	10 756	+	4 302	=	15 058
7	15 058	+	6 023	=	21 081
8	21 081	+	8 432	=	29 513
9	29 513	+	11 805	=	41 318
10	41 318	+	16 527	=	57 845
11	57 845	+	23 138	=	80 983
12	80 983	+	32 393	=	113 376
13	113 376	+	45 350	=	158 726
14	158 726	+	63 490	=	222 216
15	222 216	+	88 886	=	311 102
16	311 102	+	124 441	=	435 543
17	435 543	+	174 217	=	609 760
18	609 760	+	243 904	=	853 664
19	853 664	+	341 466	=	1 195 130

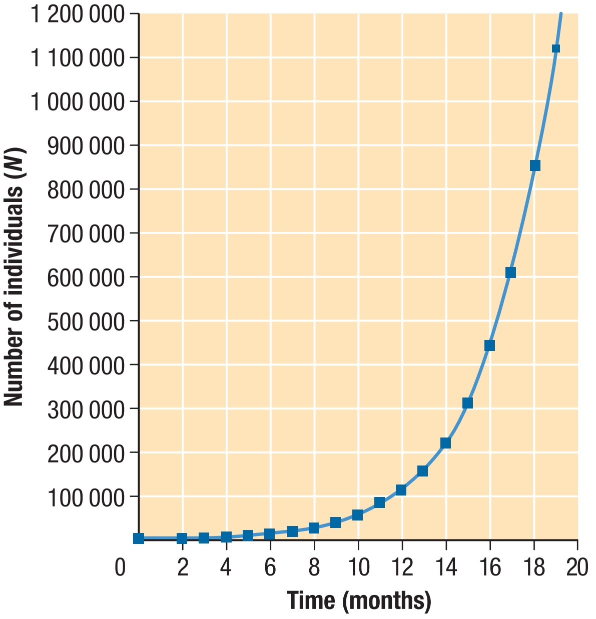


Figure 3 Exponential population growth produces a J-shaped curve when population size is plotted against time. Although the per capita growth rate (r) remains constant, the population growth increases every month because more individuals are reproducing.

Now imagine another hypothetical population, living in a comfortable abiotic environment with unlimited food and shelter. There are no predators, parasites, or disease. Under these ideal (although unrealistic) conditions, the per capita birth rate is very high, the per capita death rate is very low, and the per capita growth rate (r) is as high as it can be. This maximum per capita growth rate ($r_{\max}$) is the population's intrinsic rate of increase. Thus, under these ideal conditions, the exponential growth equation is

$$\frac{dN}{dt} = r_{\max} N$$

A population's intrinsic rate of increase is the rate at which it would increase under ideal conditions. When a population grows at its intrinsic rate of increase, the population size increases very rapidly. For a wide variety of protists and animals, $r_{\max}$ varies inversely with generation time. Species with a short generation time have a higher intrinsic rate of increase than those with a long generation time (**Figure 4**).

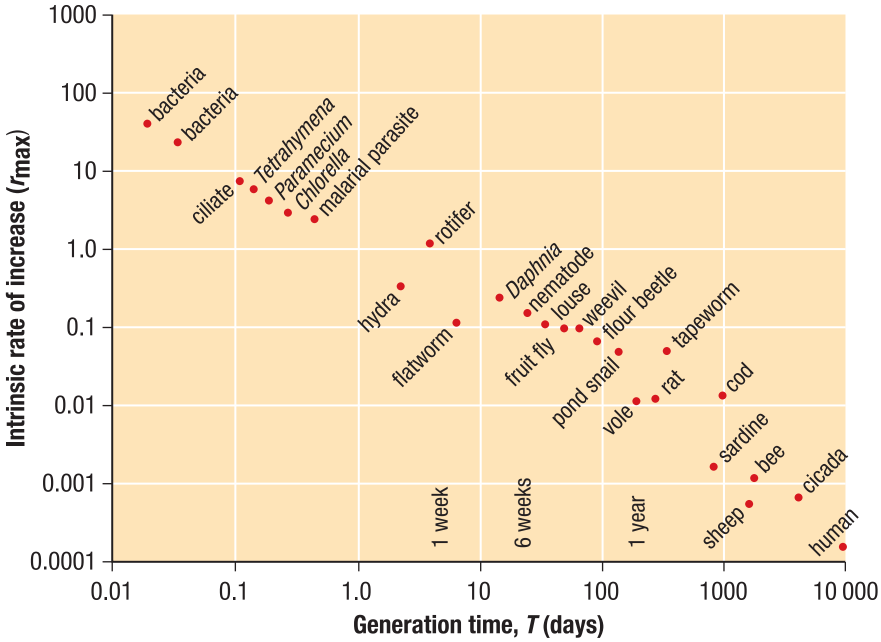


Figure 4 This graph shows the relationship between generation time and the intrinsic rate of increase (r_{max}). The intrinsic rate of increase is high for protists and animals with a short generation time and low for those, such as humans, with a long generation time.

Calculating Doubling Times

The doubling time of a population is the amount of time that is required for the population to double in size. Of course, the greater the rate of population growth is, the faster the population will double. For any population that is growing exponentially, the time that is needed for the population to double in size (the doubling time) is a constant. A useful approximation of such a population's doubling time (t_d) is given by the formula below:

$$t_d = \frac{0.69}{r}$$

For example, if a population has a growth rate of 4 % (0.04) per year, then the time that is needed for the population to double in size will be

$$t_d = \frac{0.69}{0.04}$$

$$t_d = 17.25 \text{ years}$$

In the following tutorial, you will use the exponential growth model to predict future populations.

Tutorial 1 Calculating Exponential Growth

Exponential growth can be used to predict future populations of bacteria, wildlife, and even humans.

Sample Problem 1

Populations of single-celled marine algae grow exponentially. A sample of single-celled marine algae provided an estimate of 125 000 cells on the initial sampling date. The intrinsic growth rate (r) is 0.16 per day. Calculate the following:

(a) the initial instantaneous growth rate of the population
(b) the time it will take for the population to double in size
(c) the size of the population after five doubling periods

Solution

Step 1. To calculate exponential population growth, we need to know the number of periods that are being covered and the original population. Start by making a list of the known values.

$r = 0.16$

periods covered = 5

original population (N) = 125 000 cells

The formula is $\frac{dN}{dt} = rN$.

Step 2. Calculate the initial instantaneous growth.

$$\begin{aligned}\text{Initial instantaneous growth} &= rN \\ &= 0.16 \times 125\,000 \\ &= 20\,000\end{aligned}$$

(a) When the population size is 125 000, the instantaneous growth rate is 20 000 per day.

Step 3. Calculate the time it will take for the population to double in size. Use the following formula:

$$t_d = \frac{0.69}{r}$$

$$t_d = \frac{0.69}{0.16}$$

$$t_d = 4.31 \text{ days}$$

(b) The marine algae population will double in size every 4.31 days.

Step 4. When $t_d = 4.31$ days, the initial population size is 125 000.

Complete **Table 1**.

Table 1 Marine Algae Population Growth

Doubling periods	Time (days)	Population size
0	0	125 000
1	4.31	250 000
2	8.62	500 000
3	12.93	1 000 000
4	17.24	2 000 000
5	21.55	4 000 000

(c) The size of the population after five doubling periods is 4 000 000.

Practice

1. A population of 1500 bacteria grows exponentially for three doubling periods, at a rate of 0.020 per hour, until the bacteria are killed with antibiotics.
   (a) Calculate the initial growth rate of the population. [ans: 30/h]
   (b) How long will it take for the population to double in size? [ans: 34.5 h]
   (c) What is the size of the population after three doubling times? [ans: 12 000]
   (d) What would the shape of the graph look like over time?

Limitations of the Exponential Growth Model

Environmental limitations prevent populations from experiencing continuous growth. There are limited resources to support any population. Once the individuals outnumber the resources, the population tends to drop off as individuals compete for the remaining resources. As a consequence, the per capita birth rate decreases and the per capita death rate increases.

In addition, many populations do not reproduce continuously. Instead, they have breeding periods, where there is a sudden large birth rate. In Canada, most birds, mammals, and amphibians reproduce in the spring and summer. Female northern leopard frogs, for example, deposit up to 3000 eggs in the spring, dramatically increasing the population. These frogs exhibit a geometric growth pattern in which reproduction occurs at fixed intervals and then the population declines until the next breeding period. This growth rate is determined by comparing population sizes from year to year.

As Figure 3 (page 602) shows, populations that grow exponentially result in a smooth J-shaped growth curve. The curve starts off increasing slowly, and then, as the population gets larger, it grows faster and becomes steeper. Initially, the curve that is created by geometric growth appears to be similar to the exponential curve. Even though the population fluctuates as a result of the breeding seasons, the overall trend is similar (**Figure 5**). In most populations, however, environmental limitations create another growth model—logistic growth.

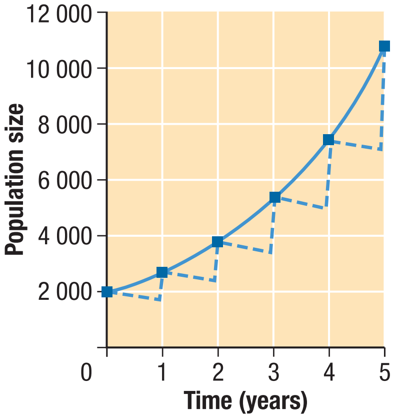


Figure 5 A geometric growth curve

Logistic Model of Population Growth

An environment provides enough resources to sustain only a finite population of any species. The maximum number of individuals that an environment can support indefinitely is its **carrying capacity (*K*)**. The carrying capacity is different for every population. It is a property of the environment that can vary from one habitat to another and even in a single habitat over time. For example, in temperate habitats, the large populations of insects in the spring and summer support large populations of insectivorous birds. However, few if any insects are available in the autumn and winter, causing a seasonal decline in the carrying capacity for birds. Autumn migrations occur in bird species as they seek more food and warmer weather. Other cycles are annual, such as the variation in the water levels in wetlands from year to year, or may span decades or longer. This **logistic model of population growth** describes growth that levels off as the size of a population reaches the carrying capacity.

carrying capacity (*K*) the number of individuals in a population that the environmental resources can support

logistic model of population growth a model that describes limited population growth, often due to limited resources or predation

To create the logistic model, we factor the impact of K into the exponential model by multiplying $r_{\max}N$ by $\frac{(K - N)}{K}$:

$$\frac{dN}{dt} = r_{\max}N\frac{(K - N)}{K}$$

If a population is very small (N much less than K), plenty of resources are available and therefore the value of $\frac{(K - N)}{K}$ is close to 1. The per capita growth rate (r) approaches the maximum possible (r_{max}), so the population growth reaches its maximum.

If a population is large (N close to K), few resources are available, the value of $\frac{(K - N)}{K}$ is small, and the per capita growth rate (r) is very low.

If the size of a population equals K, $\frac{(K - N)}{K}$ becomes 0, as does the population growth rate. This situation is defined as zero population growth.

Finally, if the size of a population (N) exceeds the carrying capacity of the habitat, K, then the population will decrease. Some organisms will die from lack of food and other resources. When graphed, this type of population growth creates an S-shaped curve, or **sigmoid curve (logistic)**. When the population is small, it shows exponential growth. However, as the population approaches the carrying capacity, the growth slows down and the curve levels off.

sigmoid curve (logistic) an S-shaped curve, typical of population growth that starts slow, accelerates or grows rapidly, and then levels out over time

The logistic model of population growth predicts an S-shaped curve for population size over time, with the population slowly approaching K and remaining at this level. The population grows slowly when the population size is small because few individuals are reproducing. It also grows slowly when the population size is large because, as the population approaches K, the per capita population growth rate is low. The population grows quickly ($\frac{dN}{dt}$ is highest) at intermediate population sizes, when a large number of individuals are breeding and the per capita population growth rate (r) is still fairly high.

In some very dense populations, accumulation of poisonous waste products may reduce survivorship and reproduction. Most natural populations live in open systems, where wastes are consumed by other organisms or flushed away. However, the buildup of toxic wastes is common in laboratory cultures of micro-organisms. For example, yeast cells ferment sugar and produce ethanol as a waste product. Thus, the alcohol content of wine usually does not exceed 13 % by volume, the point at which the ethanol concentration poisons the yeast that are vital to the winemaking process.

How well do species conform to the predictions of the logistic model? Relatively small organisms, such as *Paramecium*, some crustaceans, and flour beetles, often show an S-shaped pattern of population growth (**Figure 6(a)**). Similarly, large animals introduced into new environments may show a pattern of population growth that matches the logistic model (**Figure 6(b)**).

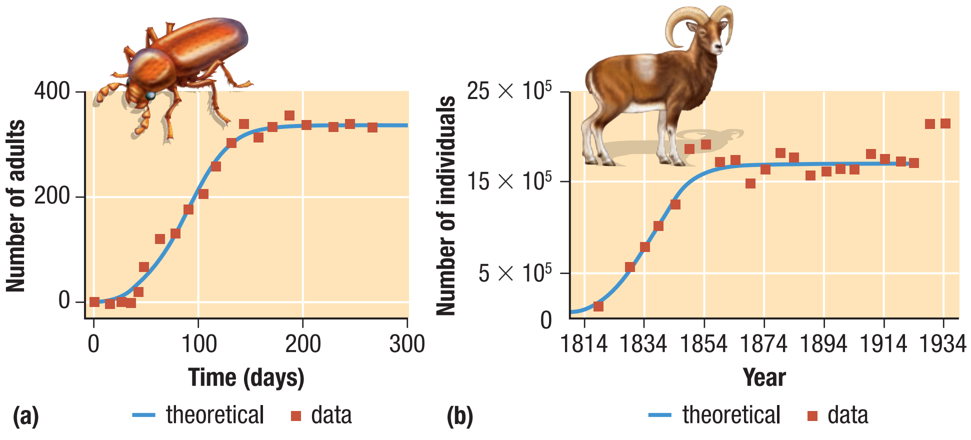


Figure 6 (a) A laboratory population of the grain borer beetle (*Rhizoperitha dominica*) showed logistic growth when its food was replenished weekly. (b) European mouflon sheep (*Ovis musimon*) introduced into Tasmania exhibited logistic population growth. The data represent five-year averages, smoothing out the annual fluctuations in population size.

Tutorial 2 Calculating Logistic Growth

The logistic model is more realistic than the exponential growth model. It is the basis for most complex models in population ecology. However, even this model simplifies the true complexities that are found in population biology.

Sample Problem 1

A population of spotted butterflies exhibits logistic growth. The carrying capacity of the population is 500 butterflies, and the maximum growth rate (r_{max}) is 0.1.

(a) Determine the population growth rates based on a population size of 50, 100, 200, 350, 480, 500, and 525 butterflies.

(b) Describe the relationship between population size and growth rate.

Solution

Step 1. (a) The following information is given:

$K = 500$

$r_{max} = 0.1$

The formula is

$$\frac{dN}{dt} = r_{max}N\frac{(K - N)}{K}$$

$\frac{dN}{dt}$ is the population growth rate at a given time

where r_{max} is the maximum growth rate

N is the population size

K is the carrying capacity of the environment

Step 2. Complete **Table 2** using the given information.

Table 2 Spotted Butterfly Population Growth

r_{max}	N	$\frac{(K - N)}{K}$	**Population growth rate**
0.10	50	$\frac{(500 - 50)}{500} = 0.90$	$0.90 \times 50 \times 0.10 = 4.5$
0.10	100	$\frac{(500 - 100)}{500} = 0.80$	$0.80 \times 100 \times 0.10 = 8$
0.10	200	$\frac{(500 - 200)}{500} = 0.60$	$0.60 \times 200 \times 0.10 = 12$
0.10	350	$\frac{(500 - 350)}{500} = 0.30$	$0.30 \times 350 \times 0.10 = 10.5$
0.10	480	$\frac{(500 - 480)}{500} = 0.04$	$0.04 \times 480 \times 0.10 = 1.92$
0.10	500	$\frac{(500 - 500)}{500} = 0$	$0 \times 500 \times 0.10 = 0$
0.10	525	$\frac{500 - 525}{500} = -0.05$	$-0.05 \times 500 \times 0.10 = -2.5$

Notice that the mathematical expression $\frac{(K - N)}{K}$ approaches zero as the population size (N) gets closer to the carrying capacity (K). Once the expression reaches zero, the population growth ceases.

(b) As the population increases, the growth rate increases as well. As the population approaches the carrying capacity, the growth rate levels off. Note that there is negative growth if the population size exceeds the carrying capacity.

Practice

A white-tailed deer population in a small forest ecosystem exhibits logistic growth. The carrying capacity is 300 deer, and $r_{max} = 0.23$.

(a) Determine the population growth rates based on population sizes of 100, 180, 200, 250, and 300 deer. [ans: 15, 17, 15, 9.6, 0.0]

(b) Explain the relationship between maximum growth rate and population size.

Limitations of the Logistic Growth Model

The logistic growth model attempts to describe the real-world relationship between population growth and carrying capacity through mathematical operations or graphs. Every model is a simplification of reality and requires assumptions to be made. The logistic growth model assumes that all individuals reproduce, die, and use resources at an identical rate. It also assumes that the carrying capacity remains constant and there are no environmental variations that might cause the carrying capacity to fluctuate.

Another assumption that the logistic growth model makes is that there is no migration and that populations do not interact with each other. In an open population, natality, mortality, immigration, and emigration all affect the growth rate of a population over a period of time. Most wild populations are considered to be open as their members can immigrate to and emigrate from populations in different locations. The human population in Canada is an open population as people can, generally, immigrate to Canada or emigrate from Canada to other countries. In a closed population, only natality and mortality affect the growth rate of the population. Immigration and emigration do not occur. Closed populations are unusual in the wild, existing only on secluded islands where individuals cannot easily travel to other populations. The human population on Earth is a closed population, since there is no immigration to, or emigration from, other planets.

In reality, very few populations meet the assumptions made by the logistic growth model and show this form of growth. Instead, populations are open, allowing interactions between biotic and abiotic factors. Populations often reach their carrying capacity, and, because of time lags as they respond to changes in environmental conditions, their size may fluctuate instead of maintaining a steady level. On a graph, this up-and-down oscillation around a fairly steady line is known as a sinusoidal curve (**Figure 7**). Occasionally, the carrying capacity can change dramatically when new organisms invade a habitat or human activities change the available resources in a short period of time.

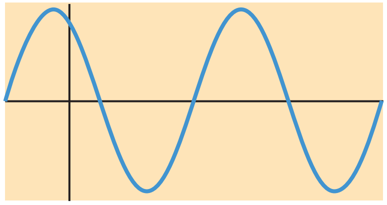


Figure 7 A sinusoidal curve oscillates in the characteristic shape of a sine wave, rising above and falling below a line with predictable regularity.

12.3 Review

Summary

- Mathematical models and graphs help ecologists predict and monitor trends in populations.
- Exponential growth and geometric growth models describe population growth when resources are assumed to be unlimited.
- There is an upper limit to the number of individuals that most environments can support. This upper limit is known as the carrying capacity of the population.
- The logistic growth model assumes that the population growth rate cannot be positive when the population size exceeds its carrying capacity.

Questions

1. A white-tailed deer population in a provincial park was estimated to be approximately 4000, with a carrying capacity of 30 000. Other than natural predators, the deer were left alone. Hunting was prohibited. After a winter in which the predators decimated the deer population, a deer population management plan was put in place. It was decided to remove the predators through hunting and trapping. Initially, the deer population flourished. Eventually, however, the deer population started to decrease. K/U T/I C
   (a) Graph the population changes over the 35-year period using the data in **Table 3**.

Table 3 Changes in a Deer Population

Year	Deer population
1	3 000
5	8 000
10	25 000
15	55 000
20	70 000
25	24 000
30	10 000
35	2 000

   (b) Using a different colour, draw a horizontal line across the graph at the carrying capacity.
   (c) Why do you think the deer population decreased after year 20, despite the fact that the predators had been removed?
   (d) Did the management plan initially seem to be effective? Why?
   (e) Without human interference and the deer management plan, what do you think would have happened to the deer population?
2. Why is exponential growth represented by a J-shaped curve? Why is logistic growth represented by an S-shaped curve? K/U
3. What is carrying capacity? Why is it an important statistic when describing an environment? K/U
4. The Asian carp is an invasive alien species that could have a catastrophic impact on the Great Lakes. Research this species to answer the following questions. T/I A
   (a) What is an invasive alien species?
   (b) Why are invasive alien species a concern?
   (c) How do scientists think that the Asian carp may enter the Great Lakes ecosystem?
   (d) Describe some of the economic concerns as a result of the Asian carp invasion.
   (e) Outline any control efforts.
5. The human population is currently doubling every 40 years. Based on what you have learned about population growth rates and carrying capacity, what questions should we be asking of our society? A T/I
6. It has been a wet, warm summer in northern Ontario, and a small population of mosquitoes is exhibiting exponential growth. The initial population size is 650, and the intrinsic growth rate is 0.450 per day. T/I
   (a) Calculate the initial instantaneous growth rate for the mosquito population.
   (b) Calculate the doubling time for the population.
   (c) How many doubling times would have to occur for the population to exceed 1 000 000? How many days does this represent?
7. A shrew population is growing continuously. The carrying capacity of its environment is 1500 individuals and its r_{max} is 1.0. Determine the population growth rates based on populations of 100, 275, 450, 600, 825, 1000, and 1500 shrews. T/I

WEB LINK

12.4 Factors That Affect Population Growth

limiting factor a factor that limits the growth of a population

density-dependent factor a factor that is influenced by population density, having a greater impact as the population density increases

density-independent factor a factor that influences population regulation regardless of population density

The interactions between organisms and their ecosystems are very complex. While many factors are interdependent, studying them individually helps us understand how they affect the growth of a population in a given ecosystem. These **limiting factors** can be abiotic or biotic, and they can cause populations to either increase or decrease in size. For example, any resource that is in short supply can, in part, determine how much the population can grow.

There are two types of limiting factors. **Density-dependent factors** are those that are related to the density of a population. **Density-independent factors** are those that are generally not related to the density of a population. Density-independent factors, such as weather and climate, affect the same proportion of individuals in a population regardless of the population density. In contrast, the effects of density-dependent factors can intensify as the size of a population increases.

Density-Dependent Factors

As the density of a population increases, the effects of density-dependent factors also increase. Examples of density-dependent factors are competition, predation, disease, and space limitations. The magnitude of these factors is directly proportional to the size of the population. As the population density decreases, the impact of the density-dependent factors usually decreases. For example, as a prey population decreases in density, there will be fewer predators because the predators have fewer food resources, so their population will also decrease.

competition an interaction in which both competing populations lose access to some resources

interspecific competition competition between members of different species

intraspecific competition competition between members of the same population for resources

predation the interaction between predator and prey

Competition is a density-dependent factor because it becomes more intense when more individuals are competing for the same resources. When resources are limited, there is constant competition for food, water, space, and shelter. Competition between different species is called **interspecific competition**. For example, in Lake Winnipeg in Manitoba, there is interspecific competition between northern pike and walleye. They both prey on the yellow perch population for food. However, the competition is only apparent if the population densities of the pike and walleye are high or the population density of the yellow perch is low. Competition is not limited to different species, however. **Intraspecific competition** occurs when members of the same species compete for resources such as food, mates, light, or shelter.

Predation, when one organism kills and eats another organism, is more competitive when the population density of the predators is high. By consuming the prey, predators increase their own population while decreasing the population density of the prey. Many moose populations in Ontario are limited by wolf predation when wolves kill and eat more moose than the number of calves that are born each year. Conversely, when wolf populations decrease, the moose population increases. Lack of predation can cause problems for the prey population, however. Without predation, the prey population can increase rapidly. This can lead to a depletion of resources and can increase the risk of disease.

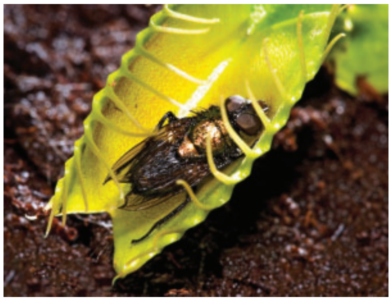


Figure 1 The Venus flytrap is a carnivorous plant that feeds on insects and spiders to help it compete in its nutrient-poor habitat.

One unusual predator is a carnivorous plant called the Venus flytrap (**Figure 1**). While it can get most of its food through photosynthesis, it has an adaptation to its nutrient-poor environment that enables it to trap and extract nutrients from small insects and spiders. Since plants cannot move around to find their food like animals can, competition for food among plants, particularly in nutrient-poor habitats, is intense. Some biologists suggest that developing the ability to be carnivorous was an adaptation that allowed the Venus flytrap to avoid interspecific competition.

Disease in a population also increases with the density of the population. High population density makes the spread of disease easier, and disease can have catastrophic effects on a population, as well as on all the populations that interact with it in an ecosystem. White-nose syndrome is a disease that affects hibernating little brown bats (**Figure 2**). The disease gets its name from the white fungus that appears around the bat's snout and body while the bat is hibernating. It has resulted in a high level of mortality and a rapid decline in the number of little brown bats in recent years. Little brown bats play an important role as predators of night flying insects. They are very efficient hunters, capable of catching over 1000 insects per hour. As bats are the top predator for insects such as mosquitoes, beetles, and moths, the fungus could potentially have a major impact on an ecosystem.

Crowding, another density-dependent factor, only occurs in high-density populations with limited space. Crowding affects the growth, size, and survival of the individuals in a population (**Figure 3**). Individuals living in extremely dense populations are unable to harvest enough resources. They grow slowly and tend to be small, weak, and less likely to survive. Gardeners understand this relationship and thin their plants to achieve a density that maximizes the number of vigorous individuals. In addition, when resources are in short supply, individuals in the population have less energy for reproduction after meeting their basic maintenance needs. Females in a crowded population may produce fewer or smaller offspring, decreasing the possibility of survival. Crowding can also affect population size by allowing disease to spread more easily and/or encouraging migration away from the original area of high density. Both situations reduce the size and density of the original population.

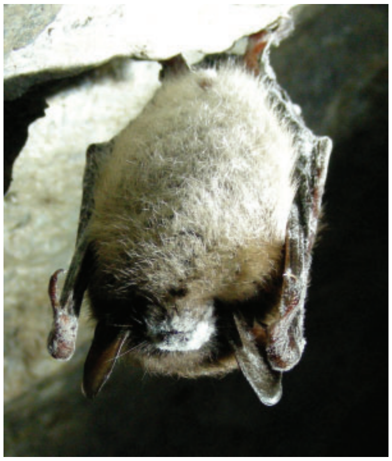


Figure 2 A disease called white-nose syndrome is killing bats. It is caused by a fungus that appeared for the first time just a few years ago.

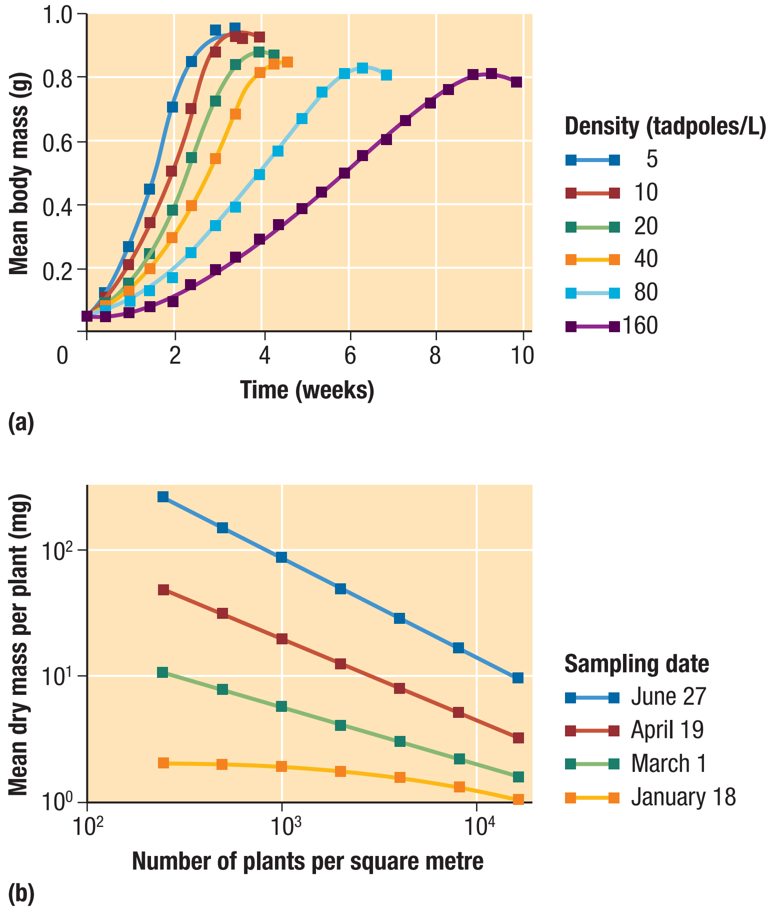


Figure 3 The effects of crowding on growth, size, and survival: (a) Tadpoles of the frog *Hoplobatrachus tigerinus* grew faster and reached larger adult body size at low densities than at high densities.
(b) The annual dune grass *Vulpia fasciculata* was smaller when plants were grown at high density. Density effects became more accentuated through time as the plants grew larger.

Research This

Don't Jump! Lemming Mythbuster

Skills: Researching, Analyzing, Evaluating, Communicating

SKILLS HANDBOOK A4.1

A 1958 nature film, *White Wilderness*, showed lemmings (**Figure 4**) leaping off a cliff into the ocean. The film led people to believe that lemmings periodically commit mass suicide by drowning when their population becomes too large. But is this true? You will discover how lemming populations change and how lemmings actually behave when their population becomes too large.

Figure 4 Lemmings often have population explosions.

1. Use the Internet and other sources to find information about the following topics:
   - the general appearance of the lemming and its natural habitat
   - how lemming populations change and why
   - how lemmings behave when their population changes

A. Fact or myth? Was the nature film accurate? Do lemmings actually commit mass suicide? K/U T/I

B. It has been said that a good story will always trump good science. Find other examples of "Hollywood science" or science myths that are widely believed. How does scientific inquiry help people understand what is fact and what is fiction? T/I

C. Why is it important for scientific documentaries to be different from Hollywood movies when dealing with science and nature? T/I

WEB LINK

Not Crowded Enough: The Allee Effect

Allee effect a density-dependent phenomenon that occurs when a population cannot survive or fails to reproduce enough to offset mortality once the population density is too low

While many density-dependent factors regulate high-density populations, some density-dependent factors reduce the population growth rate at a low population density. This phenomenon is named after the ecologist who discovered it, W.C. Allee. The **Allee effect** occurs when populations become too small. Allee noticed that all plant and animal species that reach small sizes or low densities experience a decrease in their per capita rate of population growth. This effect can produce an increased extinction risk for very small populations through reduced individual fitness.

The great auk was a large, flightless, penguin-like bird that lived along the coast of the North Atlantic Ocean (**Figure 5(a)**). It was particularly easy to catch, so it was over-hunted. The female great auk laid only one egg per year and, because of the uncontrolled over-hunting, the species was reduced to the point where it could not recover. By 1844, the great auk had become extinct.

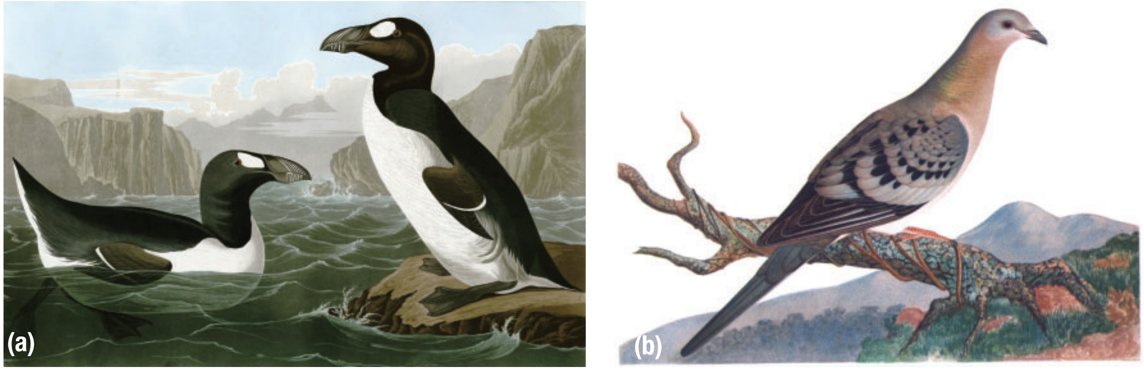


Figure 5 The Allee effect played a role in the extinctions of (a) the great auk, which was extinct by 1844, and (b) the passenger pigeon, which was extinct in 1914.

The Allee effect also played a role in the extinction of the passenger pigeon (**Figure 5(b)**). In the 1800s, there were 3 to 5 billion passenger pigeons worldwide. One-fourth of the population lived in North America, in the deciduous forests of southern Ontario, Manitoba, and eastern Canada, as well as the eastern United States. Like the great auk, passenger pigeons laid only one egg per nest and would only breed in a large colony. Commercial over-hunting for their feathers and meat, as well as destruction of their habitats, reduced their populations to the point where the species could not recover. The passenger pigeon was completely eliminated by the early 1900s. Like the great auk, the passenger pigeon's limited annual ability to reproduce prevented the species from recovering. Both the great auk and the passenger pigeon show how habitat alteration and over-hunting can endanger even a species with extremely large populations.

Small populations are at a greater risk for extinction due to the normal variations in natality and mortality, resource limitations, habitat availability, predation, competition, and catastrophic events such as forest fires and flooding. The **minimum viable population size** is the least number of individuals that ensures the continued existence of a population for a determined period of time, regardless of environmental change or disaster. If a species drops below its minimum viable population size, the chances of extinction increase dramatically. The minimum viable population size varies between species and provides ecologists with a model to predict targets for species recovery and re-introduction programs. However, minimum viable population size is only a prediction.

minimum viable population size the smallest population size that is likely to survive both predictable and unpredictable environmental variation; note that it is only a prediction

In 1941, the world population of whooping cranes had dropped to fewer than 20 individuals. Biologists were concerned that the species was in imminent danger of extinction since it was well below its minimum viable population size. Over-hunting and habitat destruction had contributed to the declining number of whooping cranes, requiring an ambitious breeding program and legal protection of the species. While still on the endangered species list, the whooping crane population has risen to 300 individuals.

Changes in habitat quality or quantity may indirectly affect the survival or reproduction of large-range animals, such as caribou and grizzly bears. These animals naturally exist at low densities and have low reproductive output. It is more difficult for them to recover when a decreased population size reduces their mating choices or opportunities, compared with other species such as deer, elk, and moose, which naturally maintain higher population densities and are more productive.

Plants that grow at low densities can suffer from the Allee effect as a result of pollen limitation. Some plant species overcome this difficulty by reproducing asexually.

Density-Independent Factors

Some populations are affected by density-independent factors that reduce population size regardless of density. If an insect population is not physiologically adapted to high temperatures, a sudden hot spell may kill 80 % of them, whether there are 100 or 100 000. Fires, earthquakes, storms, and other natural disturbances can contribute directly or indirectly to density-independent mortality.

In addition to natural disturbances, temperature fluctuations influence the growth and activities of organisms. In Canada, climate change has had a catastrophic effect on the mature pine trees in British Columbia and Alberta. The mountain pine beetle (*Dendroctonus ponderosae*) burrows into pine trees, eating the soft tissue beneath the bark (**Figure 6**). Too many beetles can overwhelm a tree and kill it. This had not been a serious problem until recently, because beetle populations were kept in check by winter frosts and temperatures that routinely dropped below −30 °C. In recent years, the winter temperatures have not been low enough to limit the beetle population significantly. A substantially higher beetle survival rate and the lack of moisture have stressed trees, reducing their ability to defend themselves against beetle attack.

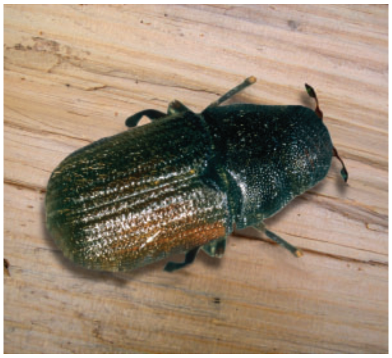


Figure 6 Mountain pine beetles have been destroying Canada's forests and making them more vulnerable to massive forest fires, such as the one that occurred in Slave Lake, Alberta, in 2011.

According to Natural Resources Canada, the area of beetle spread is expected to decline as the outbreak subsides over the next 10 years. However, the damage has been done. Current provincial government projections indicate that the infestation will have claimed about 70 % of British Columbia's mature pine trees by 2017 (**Figure 7**).

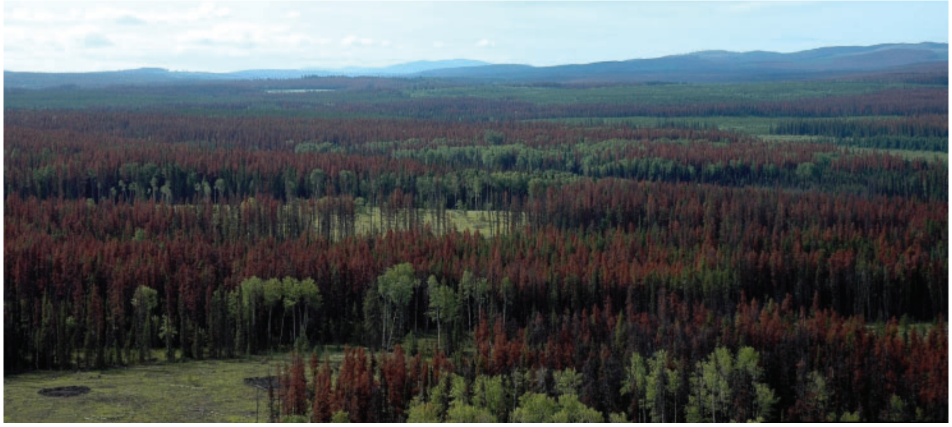


Figure 7 Several strategies are being used to control the mountain beetle population in British Columbia, including removing infested trees and controlled burns.

In Alberta, the large population of mature pine trees along the eastern slopes of the Rocky Mountains and the continuity of the pine landscape make this area highly vulnerable to beetle attack. Control efforts are slowing the rate of beetle spread, aided by local cold winter periods. Despite this fact, the area of beetle attack in Alberta is expanding at an increasing rate.

In addition to the loss of trees and the financial impact on timber production, the swaths of dead trees are emitting enormous quantities of carbon dioxide into the atmosphere as they decompose. This is further exacerbating our climate problems and creating what scientists refer to as a positive feedback loop. Positive feedback acts to amplify a situation. In the example of the pine trees, an increased level of carbon dioxide in the atmosphere has led to warmer winters, which have caused the mountain pine beetle infestation. The subsequent devastation of the pine tree population by the mountain pine beetles has caused the trees to produce more carbon dioxide, again increasing the amount of atmospheric carbon dioxide, which may potentially warm our winters even more. Over 100 million dollars of public money has been spent trying to control the spread of the mountain pine beetle, but all the experts agree that the only hope is colder winters. This is unlikely, based on the current chain of events.

This is not the only density-independent impact of warmer climates on the level of atmospheric carbon dioxide. Normally, forests take up carbon dioxide from the atmosphere through photosynthesis and then release it through respiration, decomposition, and forest fires. Under normal circumstances, trees act as "carbon sinks," absorbing and storing more carbon dioxide than they release. However, in northern Ontario and other parts of Canada, massive forest fires have turned these trees into "carbon sources," releasing the carbon that was stored in the trees. The forest fires are often caused by increased temperatures, which lead to reduced precipitation, drought, and storms (lightning strikes). The carbon dioxide from the burning trees is being released into the atmosphere at faster rates than the dead forests in British Columbia. These issues, and the potential impact of climate change on Canadian ecosystems, present great challenges for future planning and species management.

While many of the factors that were discussed in this section are very useful for understanding population dynamics, it is important to realize that population dynamics are more complex and interdependent than these models suggest. To understand complex interdependent systems, ecologists split these systems into individual components and address the components one by one. While this may be initially helpful, by studying these components of population dynamics in isolation, we may not always see the overall picture of the actual complexities of nature.

UNIT TASK **BOOKMARK**

As you work on the Unit Task on page 688, consider whether the factor you have chosen is density-dependent or density-independent.

Investigation **12.4.1**

Factors That Affect Populations (p. 629)
Now that you have read about factors affecting populations, you can complete Investigation 12.4.1. In this controlled experiment, you will create a testable question to study a population of organisms and how it reacts to a variety of factors.

12.4 Review

Summary

- Populations are dynamic. The growth of a population is limited by the presence or absence of factors that are necessary for survival.
- Density-dependent factors limit the growth of a population and are dependent on population density.
- Density-independent factors limit the growth of a population regardless of population density.

Questions

1. Classify each situation as density-dependent or density-independent, and explain your reasoning. Share your ideas with a classmate. Does your classmate agree with your reasoning? Why or why not? K/U T/I C
   (a) A drought decreases the water level of a lake, thus decreasing its carrying capacity.
   (b) Lynx prey on snowshoe hares. An increase in the snowshoe hare population causes an increase in the lynx population.
   (c) A forest fire destroys a large amount of habitat in a provincial park.
   (d) Due to the introduction of a new species of fish, a lake becomes crowded and some species do not survive.
   (e) The use of pesticides thins the shells of peregrine falcon eggs and dramatically reduces their population size.
   (f) Increased water temperature causes many aquatic organisms to die.
2. A few members of a population have a favourable habitat, with few predators and unlimited resources. However, their population growth rate is slower than the population growth rate of the previous generation. What is a possible explanation for this situation? K/U
3. Use the Internet to research white-nose syndrome. Using the following questions as a guide, create a pamphlet that Natural Resources Canada could use to help the general public better understand the problem and potential impact on biodiversity. T/I C
   (a) What is white-nose syndrome, and what causes it?
   (b) What unusual behaviours do infected bats exhibit?
   (c) Which bats are being infected?
   (d) Where has white-nose syndrome spread in the United States and Canada?
   (e) What is being done about it? What plans are in place?
   (f) Why do we need to protect bats?
4. Why might the birth and death rates of a white-tailed deer population in the Carolinian forest of southern Ontario be a density-dependent factor? K/U T/I
5. Compare and contrast density-dependent and density-independent factors using examples. K/U
6. Carnivorous plants are plants that derive some or most of their nutrients from trapping and consuming insects and spiders (**Figure 8**). Using the Internet, research and answer the following questions. T/I C

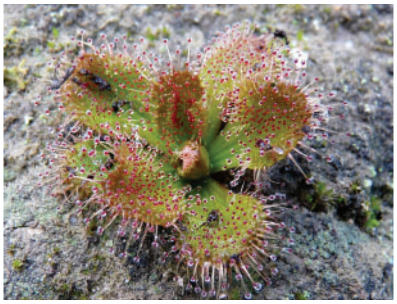


Figure 8 The sundew is a carnivorous plant that is found all over the world, including Canada. It has drops of sticky fluid on the tips of its hairy leaves. Insects try to eat the fluid and become trapped.

   (a) There are five basic trapping mechanisms that are found in carnivorous plants. Describe each mechanism, and give an example of a plant that uses it.
   (b) What is the difference between a carnivorous plant and a protocarnivorous (borderline) plant?
   (c) Choose your favorite carnivorous plant, and create a poster that includes the following information:
      - a description of the plant, including its prey selectivity, trapping mechanism, and digestion
      - its scientific classification
      - its habitat
      - its conservation status and what is being done to conserve it
      - a picture of the plant

WEB LINK

12.5 Interactions between Individuals

coevolution a process in which one species evolves in response to the evolution of another species

Individuals within a population do not live in isolation. They interact with members of their own species (intraspecific) and with members of other species (interspecific). Interactions between species change constantly, but all of these interactions occur between individuals. They usually benefit or harm the individuals involved, although some are neutral. Many of the interspecific interactions that affect the individuals' survival and reproduction are the product of long-term evolutionary adaptation. This biological **coevolution** happens when individuals of two or more species influence each other's reproductive success. Each individual of one species exerts selective pressures on individuals of the other species, thereby influencing their evolution. For example, the evolution of long bills or sickle-shaped bills in some hummingbirds match the long or sharply curved flowers that they pollinate (**Figure 1**).

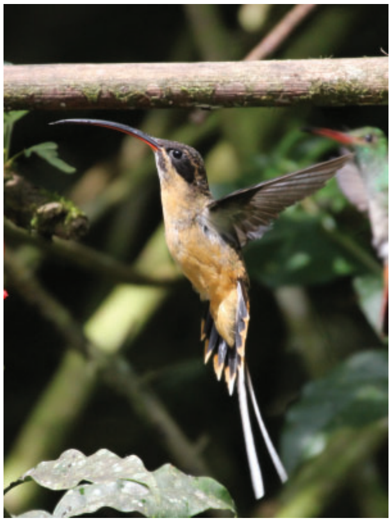


Figure 1 This tawny-bellied hermit from South America has a long, curved bill that has coevolved to match the size and shape of the flowers that it feeds on, and pollinates.

Coevolutionary relationships between pairs of organisms can take the forms listed below. **Table 1** summarizes and gives examples of these relationships.

- predation, in which an organism feeds on another organism
- **herbivory**, in which an organism feeds on a plant
- **mutualism**, in which the relationship is mutually beneficial
- **parasitism**, in which the parasite benefits from the host while reducing the host's fitness in some way
- competition, in which both organisms lose access to resources
- **commensalism**, in which one organism receives benefits from the other organism without damaging it

herbivory the interaction between herbivorous animals and the plants that they eat

mutualism an interaction in which both partners benefit

parasitism an interaction in which one species benefits and the other is harmed

commensalism an interaction in which one species benefits and the other is unaffected

Table 1 Population Interactions and their Effects

Interaction	Effects on interacting populations		Example
predation	+/–	Predators gain nutrients and energy; prey are killed or injured.	northern lynx (predator) and snowshoe hare (prey)
herbivory	+/–	Herbivores gain nutrients and energy; plants are killed or injured.	white-tailed deer (herbivore) and foliage
mutualism	+/+	Both populations benefit.	honey bee (pollinator) and flowering plants
parasitism	+/–	Parasites gain nutrients; hosts are injured or killed.	mistletoe, which attaches to a tree and takes water and nutrients from its host; usually stunts growth but can kill the tree with heavy infestation
competition	–/–	Both competing populations lose access to some resources.	trees in a forest competing for light
commensalism	+/0	One population benefits; the other is unaffected.	moss, which grows on a tree, getting the light and nutrients it needs while the tree is unaffected

Predation and Herbivory

Because animals acquire nutrients and energy by consuming other organisms, predation and herbivory are likely the most evident examples of coevolution in ecological communities. Both predators and herbivores have evolved characteristics that enable them to feed effectively. For example, carnivores use sensory systems to locate their animal prey and specialized behaviours and anatomical structures to capture and consume it. Some rattlesnakes, such as species in the genus *Crotalus*, use heat sensors on pits in their face to detect warm-blooded prey (**Figure 2**). A rattlesnake delivers venom through fangs (hollow teeth) by open-mouthed strikes on prey. Then it waits for the venom to take effect. It uses chemical sensors on the roof of its mouth to follow the scent trail left by its dying prey. The venom is produced in the snake's salivary glands. The venom contains neurotoxins that paralyze the prey, as well as protease enzymes that begin to digest it. Elastic ligaments connecting the bones of the snake's jaw (mandibles) to one another, and the mandibles to the skull, allow the snake to open its mouth very wide to swallow prey larger than its head.

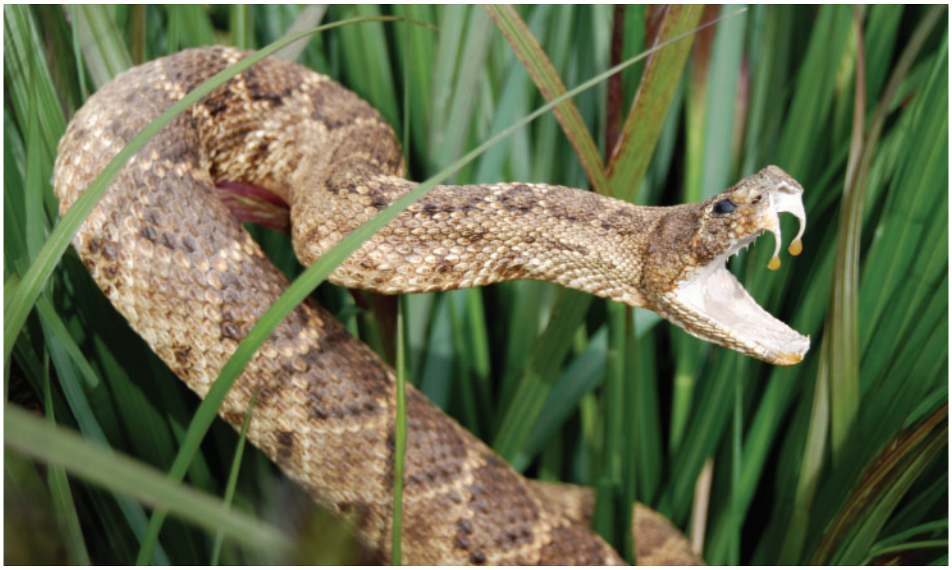


Figure 2 The rattlesnake has adaptations that allow it to sense the warmth of its prey, hollow fangs that inject venom to kill the prey, and jaws that allow it to swallow prey that is larger than its head.

Herbivores have comparable adaptations for locating and processing food plants. Insects use chemical sensors on their legs and mouthparts to identify edible plants, and they use sharp mandibles or sucking mouthparts to consume plant tissues or sap. Herbivorous mammals have specialized teeth to harvest and grind tough vegetation. Some herbivores, such as farmer ants, sheep, or termites, co-opt other species to gain access to nutrients locked up in plant materials.

All animals select food from a variety of potential resources. Some species, described as specialists, feed on one or just a few types of food. For example, pandas only eat bamboo, and koalas eat the leaves of only a few of the many available species of *Eucalyptus*. These animals have been able to survive as specialists because they live in forest habitats where their food sources (bamboo and eucalyptus trees) are plentiful and competition is low. Other species, described as generalists, have broader tastes and are therefore more adaptable to changing conditions and varying habitats. Crows (genus *Corvus*) eat food ranging from grain to insects to carrion. Grizzly bears (*Ursus arctus*) and pigs (genus *Sus*) are also omnivorous.

How does an animal select its food? Mathematical models, collectively described as optimal foraging theory, predict that an animal's diet is a compromise between the costs and benefits associated with different types of food. Assuming that animals try to maximize their energy intake at any meal, their diet should be determined by the ratio of costs to benefits: the costs of obtaining food versus the benefits of consuming it. Costs are the time and energy needed to pursue, capture, and consume a particular kind of food. Benefits are the energy provided by this food. A cougar (*Puma concolor*) invests more time and energy hunting a mountain goat (*Oreamnos americanus*) than it does hunting a jackrabbit (*Lepus townsendii*), but the payoff for the cougar is a bigger meal. One important element in food choice is the abundance of prey. Encounter rate is usually influenced by population density and can influence a predator's diet. For the cougar, the encounter rate determines the time between jackrabbits. When jackrabbits are abundant, they can be a more economical target than larger, scarcer prey.

Food abundance affects food choice. When prey is scarce, animals often take what they can get, settling for food that has a higher cost-to-benefit ratio. When food is abundant, animals may specialize, selecting types of food that provide the largest energy return. For example, bluegill sunfish eat *Daphnia* and other small crustaceans. When the crustacean density is high, bluegills hunt mostly large *Daphnia*, which provide more energy for their effort. When the crustacean density is low, they eat *Daphnia* of all sizes (**Figure 3**).

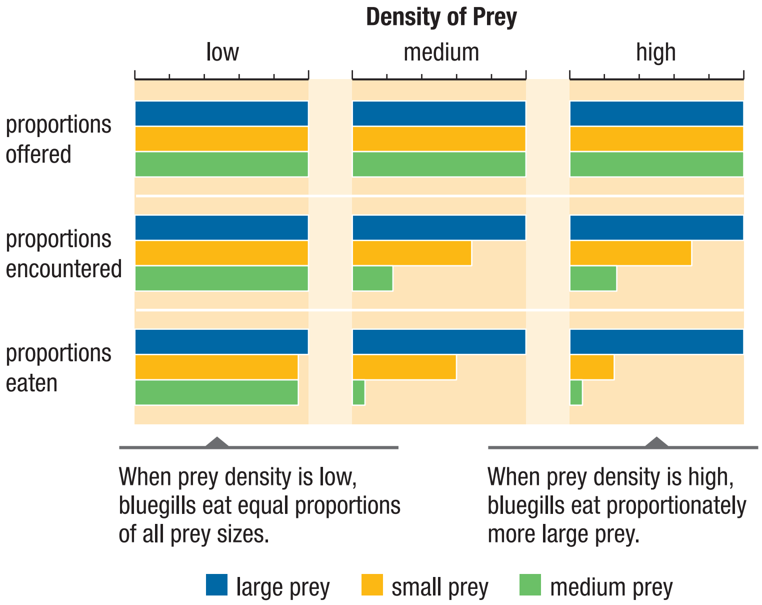


Figure 3 The bluegills' food choice varies with the density of their prey, but they always prefer the largest prey available.

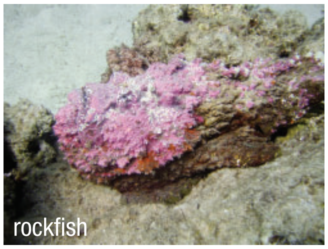
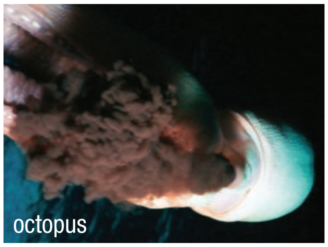
Defence Mechanisms

Predation and herbivory have a negative impact on the species being eaten, so animals and plants have evolved mechanisms to avoid being caught and eaten. These defence mechanisms include camouflage, behavioural defences, chemical defences, and **mimicry** (one species evolves to resemble another species). Some plants use spines, thorns, or irritating hairs to protect themselves from herbivores. Plant tissues often contain poisonous chemicals that deter herbivores from eating them. For example, some chemicals mimic the structure of insect hormones, disrupting the development of the insects that eat them. Most of the poisonous chemicals are volatile, giving plants their particular odours. Some herbivores have developed the ability to recognize these odours and avoid toxic plants, so the plants increase their production of toxic compounds in response to herbivore feeding. For example, potato and tomato plants that are damaged by herbivores have higher levels of protease-inhibiting chemicals. These compounds prevent herbivores from digesting the proteins they have eaten, reducing the food value of the plants.

mimicry a form of defence in which one species evolves an appearance that resembles the appearance of another species

Any adaptation that is used by prey increases its chances of survival. Some adaptations are defence mechanisms, which can give the prey an advantage against its predators (**Table 2**, next page).

Table 2 Defence Mechanisms

Defence mechanism	Example	
Camouflage: An organism mimics the patterns of its environment.	• Rockfish use disruptive coloration (breaking up the shape and destroying the outline of an object) to hinder detection and to blend into the background.	
Chemical defence: An organism is chemically unattractive, either by releasing noxious odours or by concentrating poisonous chemicals in its body.	• Skunks and bombardier beetles produce and spray a noxious chemical. • Monarch butterflies use potent plant toxins to make them distasteful to predators.	
Behavioural defence: This defence can be passive (such as hiding, freezing, or playing dead) or active (such as fleeing, herding, mobbing, or using distraction displays).	• Rabbits use both freezing and hiding to avoid becoming prey. • Muskoxen herd in a tight defensive formation, on alert with their horns toward the predator. • Birds mob and harass a predator to protect their young. • Squid and octopuses use ink clouds as a form of display distraction.	
Mimicry: One species evolves to resemble another. There are two types: Batesian and Mullerian. In Batesian mimicry, a palatable or harmless species (the mimic) resembles an unpalatable or poisonous one (the model). In Mullerian mimicry, two or more unpalatable species that share common predators look the same.	• The harmless Drone fly is a Batesian mimic of the stinging honeybee. • The Viceroy and the Monarch butterflies use Mullerian mimicry. They are both unpalatable and look very similar.	
Spines and armour: Various animals and plants have hard, thorny, or needle-like structures.	• The North American porcupine releases hairs that have been modified into sharp, barbed quills. When the quills are stuck in a predator, they cause severe pain and swelling. • The leopard tortoise lives inside a hard protective shell. • Plants such as the prickly pear cactus use spines for protection, but other organisms can also use the spines to their advantage.	

Population Cycles

Predation is an example of an interspecific interaction in which the population density of one species (predator) increases while the population density of the other species (prey) decreases. The predator-prey relationship can have a significant impact on the size of both populations. Fluctuations in the predator population follow fluctuations in the prey population through time, with the prey population increasing while the predator population is still decreasing and the prey population decreasing while the predator population is still increasing. While it might seem that the predator drives the fluctuations in the prey population, a time lag between the responses of the populations suggests that other factors also affect this relationship.

Figure 4 shows an example of how predator-prey interactions may contribute to the density-dependent regulation of both populations. The numbers of lynx (red line) and snowshoe hare (blue line) are based on the counts of pelts that trappers sold the Hudson's Bay Company over a 90-year period. The number of hares in the population rose and fell fairly regularly over each 10-year period. The population of lynx, whose diet staple was primarily snowshoe hares, tended to rise and fall just a year or two behind the changes in the hare population. Because of the fluctuations in the population, the line on the graph is a sinusoidal curve.

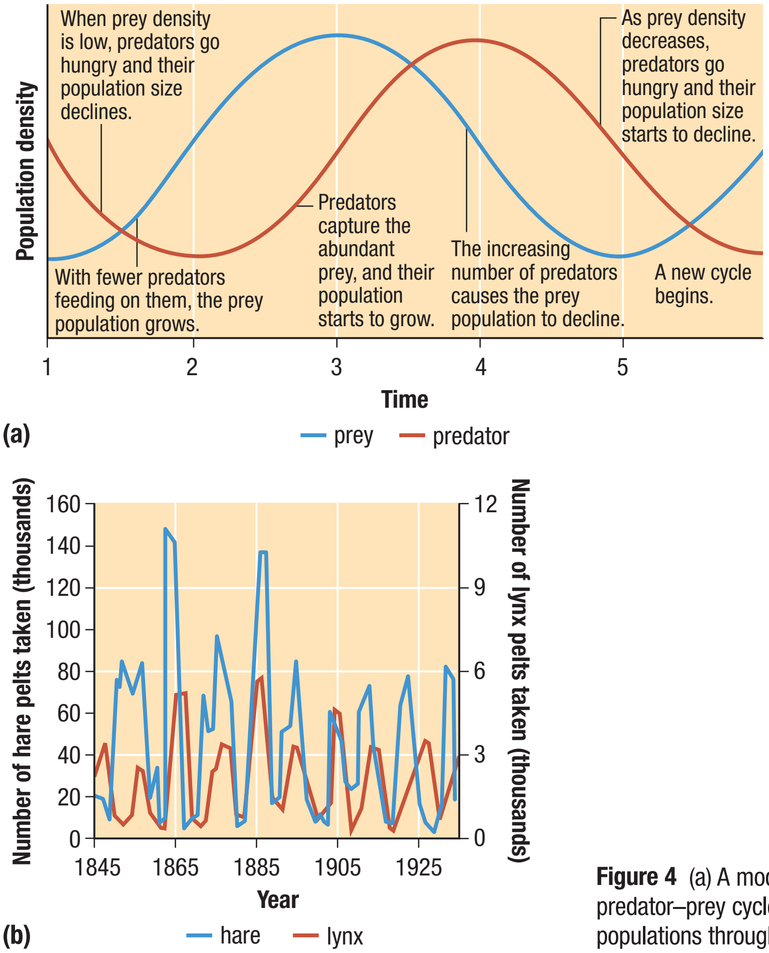


Figure 4 (a) A model of the predator–prey cycle; (b) lynx and hare populations through time

While the lynx and hare population cycle is often cited as a classic example of population cycles, snowshoe hare populations exhibit similar 10-year fluctuations even on islands where lynx are absent. To further complicate the situation, another factor that affected the fluctuations was the number of pelts purchased by the Hudson's Bay Company. Fur prices often influenced the number of animals trapped. This economic reality brought into question the relationship between the number of pelts and the actual population densities of the lynx and snowshoe hares. Recent research shows that cycles in the snowshoe hare population are caused by complex interactions between the snowshoe hares, their food sources, and their predators.

Other variables that can affect the cycling of population size include catastrophic natural events, changes in climate, and human interference, such as the addition of non-native species and habitat destruction. In Australia, for example, populations of kangaroos, which have few natural predators, were controlled by periodic droughts. Populations have increased dramatically since European settlement due to the introduction of European farming methods. The farmers cleared the forests, and the kangaroos thrived. The farmers also introduced irrigation, providing a steady source of water for the kangaroos. Consequently, a national kangaroo management plan has been established to ensure both a healthy kangaroo population and the sustainability of the Australian environment.

Investigation 12.5.1

Investigating Predator–Prey Cycling (p. 630)

You have learned about predator–prey cycles and other factors that affect populations. In this observational study, you will learn about the interactions between the wolf and moose populations on Isle Royale.

Competition

Different species that use the same limiting resources experience interspecific competition (competition between species). Competing individuals may experience increased mortality and decreased reproduction, responses similar to those for intraspecific competition. Interspecific competition can reduce the size and population growth rate of one or more of the competing populations.

Community ecologists identify two main forms of interspecific competition: interference and exploitive competition. In **interference competition**, individuals of one species harm individuals of another species directly. Animals may fight for access to resources, as when lions chase smaller predators such as hyenas, jackals, and vultures from their kills. Many plant species, including creosote bushes, release toxic chemicals into the soil. These chemicals prevent other plants from growing nearby.

In **exploitative competition**, two or more populations use (or exploit) the same limiting resource; therefore, the presence of one species reduces the resource availability for the other species. Exploitative competition does not necessarily involve snout-to-snout or root-to-root confrontations. In the deserts of the American Southwest, for example, many bird and ant species eat mainly seeds, and each seed-eating species may deplete the food supply that is available to the others without necessarily encountering the others. In Ontario, fast-growing seedlings create shade, using more of the available sunlight and reducing the survival of ground-cover plants in their vicinity.

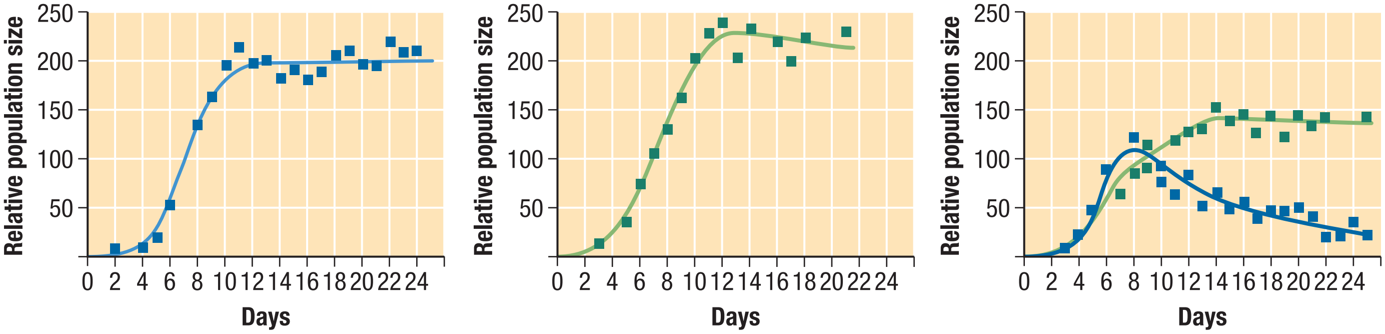
interference competition competition in which all the individuals have equal access to resources; the fitness of some individuals is reduced by the presence of others

exploitative competition competition in which all the individuals have equal access to resources; some have superior ability to gather resources

Competition and Niches

In the 1920s, the Russian mathematician Alfred J. Lotka and the Italian biologist Vito Volterra independently proposed a model of interspecific competition, modifying the logistic equation to describe the effects of competition between two species. In their model, an increase in the size of one population reduces the growth rate of the other population.

In the 1930s, a Russian biologist, G.F. Gause, tested the model experimentally. He grew cultures of two *Paramecium* species (ciliate protozoans) under constant laboratory conditions, regularly renewing their food and removing wastes. Both species fed on bacteria suspended in the culture medium. When grown alone, each species exhibited logistic growth (**Figure 5(a)** and **(b)**). When grown together in the same dish, *Paramecium aurelia* almost completely eliminated *Paramecium caudatum* (**Figure 5(c)**). These results inspired Gause to define the competitive exclusion principle. According to this principle, populations of two or more species cannot coexist indefinitely if they rely on the same limiting resources and exploit these resources in the same way. One species inevitably harvests resources more efficiently; produces more offspring than the other; and, by its actions, negatively affects the other species.



(a) *P. caudatum* alone **(b)** *P. aurelia* alone **(c)** mixed culture

Figure 5 G.F. Gause performed experiments to observe interspecific competition in *Paramecium*. (a) and (b) When each species was raised alone, both species reached a stable population size. (c) When the species were raised together, *Paramecium aurelia* persisted while the population of *Paramecium caudatum* declined.

Ecologists have developed the concept of the ecological niche to visualize resource use and the potential for interspecific competition in nature. They define a population's niche by the resources it uses and the environmental conditions it requires over its lifetime. In this context, niche includes food, shelter, and nutrients, as well as non-depletable abiotic conditions, such as light intensity and temperature. In theory, an almost infinite variety of conditions and resources could contribute to a population's niche. In practice, ecologists usually identify the critical resources for which populations might compete. Sunlight, soil moisture, and inorganic nutrients are important resources for plants, so differences in leaf height and root depth, for example, can affect a plant's access to these resources. Food type, food size, and nesting sites are important for animals. Often, when several species coexist, they use food and nest resources in different ways.

fundamental niche the range of conditions and resources that a population can possibly tolerate and use

realized niche the range of conditions and resources that a population actually uses in nature

Ecologists distinguish the **fundamental niche** of a species (the range of conditions and resources that the species can tolerate and use) from its **realized niche** (the range of conditions and resources that the species actually uses in nature). The realized niche of a species is smaller than its fundamental niche, partly because all tolerable conditions are not always present in a habitat and partly because some resources are used by other species. We can visualize competition between two populations by plotting their fundamental and realized niches with respect to one or more resources (**Figure 6**). If the fundamental niches of two populations overlap, the species might compete in nature.

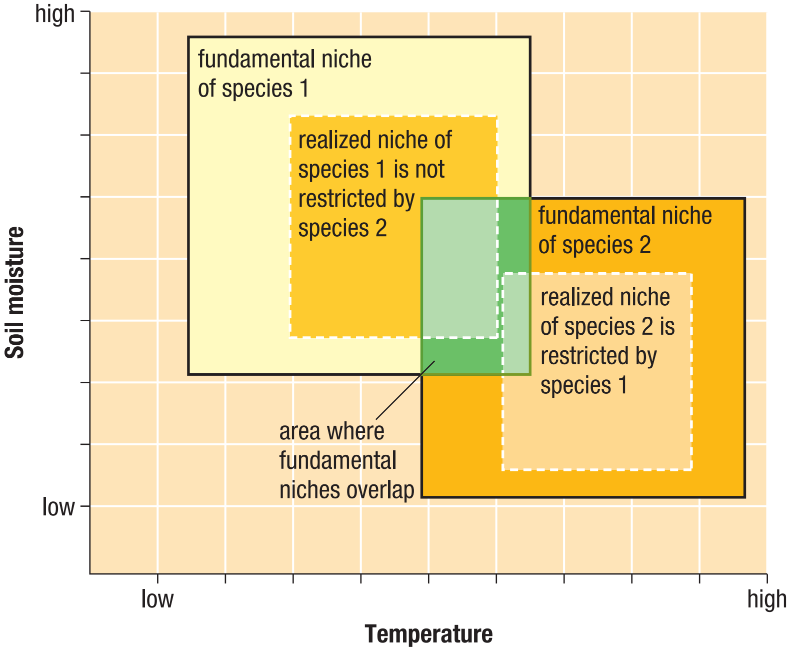


Figure 6 In this hypothetical example, both species (1 and 2) can survive intermediate temperature conditions, as shown by the shaded area where the fundamental niches overlap. However, because species 1 occupies most of the overlap zone, its realized niche is not affected that much by species 2. In contrast, the realized niche of species 2 is restricted by species 1.

Resource Partitioning

resource partitioning a situation in which several species that live in the same place use different resources or use the same resources in different ways

Resource partitioning occurs when several species that live in the same place use different resources or the same resources in different ways. Although plants may compete for water and dissolved nutrients, they may avoid competition by partitioning these resources, collecting them from different depths in the soil (**Figure 7**, next page). This allows coexistence of different species. Resource partitioning is also seen in animals. For example, Thomson's gazelles live in African savannas and grassland habitats where they are dependent on short grasses. They coexist in areas with zebras and wildebeests that eat the tall grasses. The gazelles follow the zebras and wildebeests as they eat the taller grasses that cover their food source.

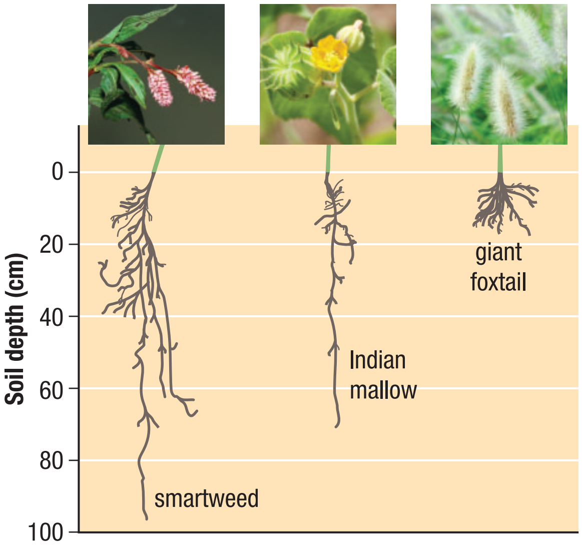


Figure 7 The root systems of three plant species that grow in abandoned fields partition water and nutrient resources in the soil. Smartweed (*Polygonum pensylvanicum*) has a deep taproot that branches at many depths, Indian mallow (*Abutilon theophrasti*) has a moderately deep taproot, and giant foxtail grass (*Setaria faberi*) has a shallow root system.

Data on resource partitioning suggest, but do not prove, that interspecific competition is an important selective force in nature. To demonstrate conclusively that interspecific competition limits natural populations, the presence of one population must be shown to reduce the population size or density of its presumed competitor. In a classic field experiment, Joseph Connell examined competition between two barnacle species. Connell first observed the distributions of both species of barnacles in undisturbed habitats to establish a reference baseline. *Chthamalus stellatus* is generally found in shallow water on rocky coasts, where it is periodically exposed to air. *Balanus balanoides* generally lives in deeper water, where it is usually submerged (**Figure 8(a)**).

In the absence of *Balanus* on rocks in deep water, larval *Chthamalus* colonized the area and produced a flourishing population of adults (**Figure 8(b)**). *Balanus* physically displaced *Chthamalus* from these rocks. Thus, interference competition from *Balanus* prevents *Chthamalus* from occupying areas where it would otherwise live. On the other hand, removal of *Chthamalus* from rocks in shallow water did not result in colonization by *Balanus* (**Figure 8(c)**). *Balanus* apparently cannot live in habitats that are frequently exposed to air. Connell concluded that there was competition between the two species. However, competition was asymmetrical because *Chthamalus* did not affect the distribution of *Balanus*, whereas *Balanus* had a substantial effect on *Chthamalus*.

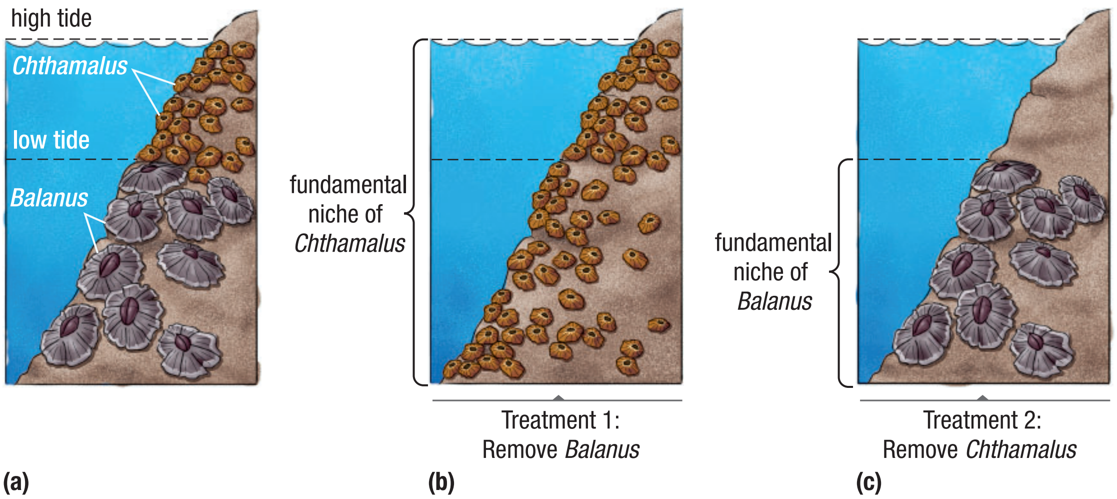

high tide
Chthamalus
low tide
Balanus
fundamental niche of Chthamalus
Treatment 1: Remove Balanus
fundamental niche of Balanus
Treatment 2: Remove Chthamalus
(a)
(b)
(c)

Figure 8 A demonstration of competition between two species of barnacles. (a) Before the experimental treatments, both species exist in their realized niches. (b) In the absence of *Balanus*, *Chthamalus* occupies both shallow water and deep water. (c) In the absence of *Chthamalus*, *Balanus* still occupies only deep water.

Symbiosis

Symbiosis occurs when one species has a physically close ecological association with another (from *sym* meaning "together," *bio* meaning "life," and *sis* meaning "process"). Biologists define three types of symbiotic interactions: mutualism, commensalism, and parasitism (Table 1, page 616).

Mutualism

In mutualism, both partners benefit. Mutualism appears to be common and includes coevolved relationships between flowering plants and animal pollinators. Animals that feed on a plant's nectar or pollen carry the plant's gametes from one flower to another. Similarly, animals that eat fruits disperse the seeds by "planting" them in piles of nutrient-rich feces. Mutualistic relationships between plants and animals do not require active cooperation, since each species simply exploits the other for its own benefit.

Some associations between bacteria and plants are mutualistic. Perhaps the most important of these associations is between the soil bacteria *Rhizobium* and leguminous plants, such as peas, beans, and clover. The roots of these plants provide a necessary host for the bacteria. The bacteria fix nitrogen, providing a critical nutrient for the plants.

Mutualistic relationships between animal species are common. Small cleaner fish feed on parasites that are attached to the mouth, gills, and body of larger fish. Parasitized fish hover motionless while cleaners remove their parasites. The relationship is mutualistic because the cleaner fish get a meal and the larger fish are relieved of parasites.

The relationship between the bull's horn acacia tree (*Acacia cornigera*) of Central America and a species of small ants (*Pseudomyrmex ferruginea*) is a highly coevolved mutualism (**Figure 9**). Each acacia tree is inhabited by an ant colony, which lives in the tree's swollen thorns. Ants swarm out of the thorns to sting, and sometimes kill, herbivores that touch the tree. Ants also clip any vegetation that grows nearby. Acacia trees that are colonized by ants grow in a space that is free of herbivores and competitors. They grow faster and produce more seeds than trees that are not colonized. In return, the trees produce sugar-rich nectar that is consumed by adult ants, as well as protein-rich structures that the ants feed to their larvae. Ecologists describe the coevolved mutualism between these species as obligatory, at least for the ants, because the ants cannot subsist on any other food source.

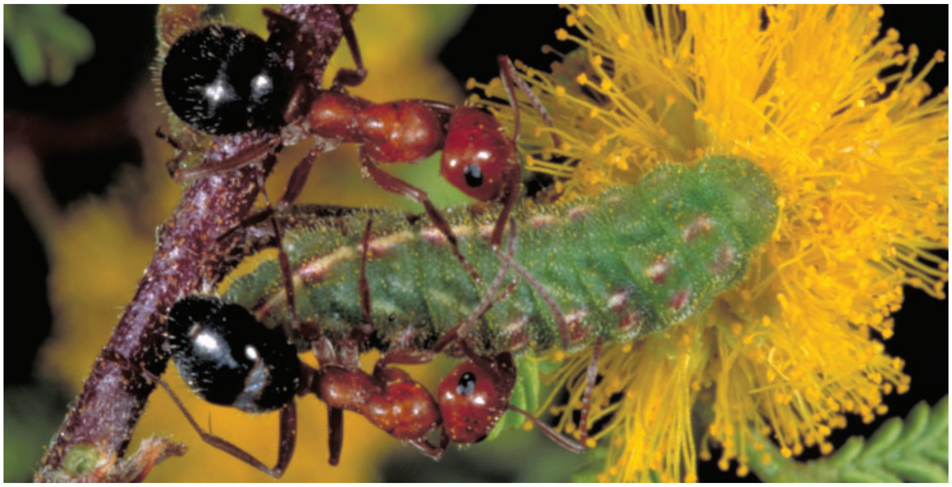


Figure 9 Ants have many cooperative relationships with other insects. In this example, the ant provides some protection from other insects for the acacia flower and the caterpillar. In return, the ant can sip from nectar glands in the caterpillar, which feeds on the flowers.

Several species of yucca plants (*Yucca* species) are pollinated exclusively by one species of moth (*Tegeticula* species). The adult moth appears at the time of year when the plant is flowering. A female yucca moth uses highly modified mouthparts to gather the sticky pollen and roll it into a ball. She carries the pollen to another flower, pierces its ovary wall, and lays her eggs. She then places the pollen into the opening of the stigma. These species are so mutually interdependent that the larvae of each moth species can feed on only one species of yucca, and each yucca plant can be pollinated by only one species of moth. Most plant-animal mutualisms are less specific.

The bond that exists between humans and cats or humans and dogs living in the same home is another example of mutualism. The cats and dogs are dependent on the humans for their survival, and the humans become attached to them. Both benefit from the relationship.

Commensalism

In commensalism, one species benefits and the other is unaffected by the interactions. Commensalism appears to be rare in nature because few species are unaffected by interactions with another species. One possible example is the relationship between cattle egrets (*Bubulcus ibis*) and the large grazing mammals they associate with (**Figure 10**). Cattle egrets eat insects and other small animals that their commensal partners flush from the grass. Feeding rates of cattle egrets are higher when they associate with large grazers than when they do not. The birds clearly benefit from this interaction, but the presence of the birds has no apparent positive or negative impact on the mammals.

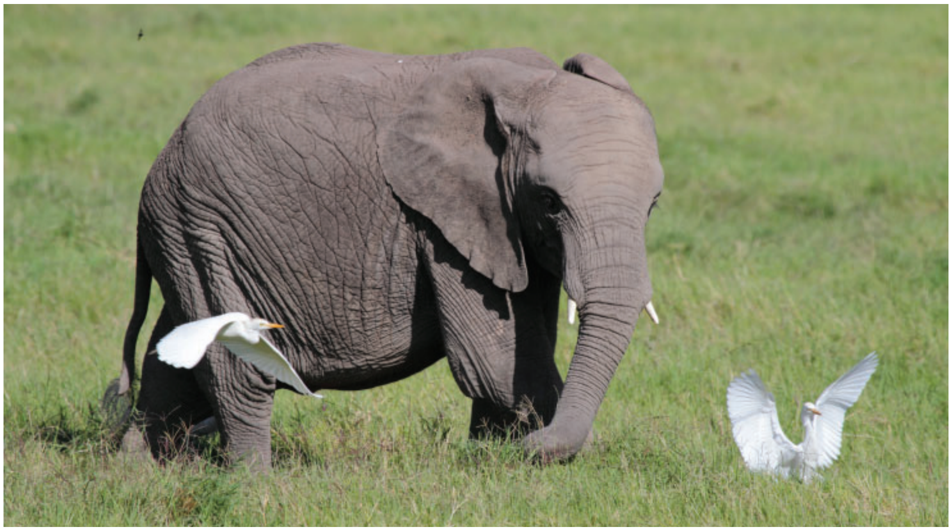


Figure 10 Cattle egrets feed on insects and other small animals that are flushed from the grass by the movements of large grazing animals, such as African elephants (*Loxodonta africana*).

Parasitism

In parasitism, one species benefits and the other species is harmed. Parasite-host relationships are often considered to be specialized predator-prey relationships because one population of organisms feeds on another. Parasites rarely kill their host, however, since they need their host to complete their life cycle. The giant kidney worm (*Dioctophyme renale*), for example, infects only the right kidney of the mink. Over time, the worm consumes the entire interior of the right kidney while releasing eggs into the urine. However, the mink can function solely on its left kidney, even after its entire right kidney has been destroyed.

Humans can play host to over 1000 different parasites, such as tapeworms and head lice. Some parasites, such as the schistosome parasite that causes swimmer's itch, do little to no harm to a human. The schistosome parasite is a blood parasite that is found in water. Its intended host is a duck. Unfortunate swimmers pick up the parasite by accident, and their bodies have an autoimmune reaction to its presence. It is annoying and itchy but otherwise harmless. However, some parasites, such as the *Plasmodium falciparum* that causes malaria, can be very harmful to humans. The parasite is passed on to humans through infected mosquitoes.

Not all parasites feed directly on their host's tissues. Some bird species are brood parasites, laying their eggs in the host's nest. It is quite common for female brown-headed cowbirds or canvasback ducks to lay their eggs in the nests of other species of birds, usually songbirds such as warblers.

The feeding habits of insects called parasitoids fall somewhere between true parasitism and predation (**Figure 11**). A female parasitoid lays her eggs in a larva or pupa of another insect species, and her young consume the tissues of the living host. Because the hosts that are chosen by most parasitoids are highly specific, agricultural ecologists often try to use parasitoids to control populations of insect pests.

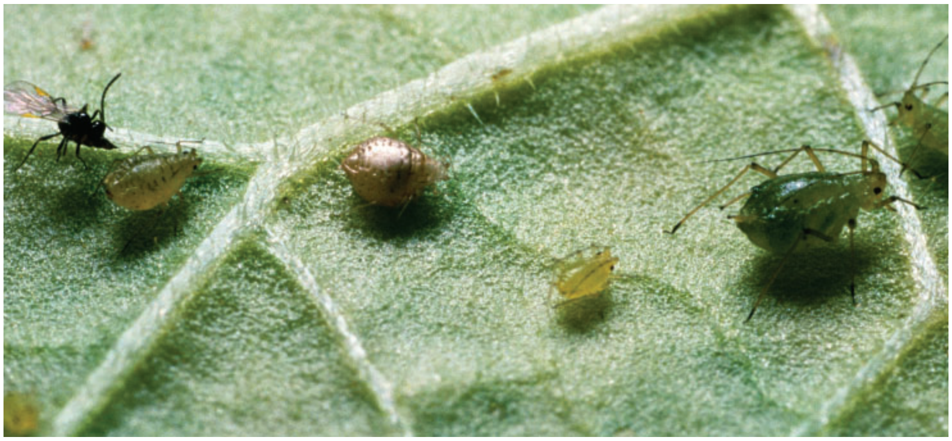


Figure 11 This parasitoid wasp (black, far left) lays its eggs in an aphid. The aphid lives as the egg is developing. When the wasp larva hatches, however, it eats the aphid from within. The aphid becomes "mummified," as seen in the centre. The wasp larva builds a cocoon inside the aphid, emerging as an adult after about 15 days. The wasp can be used to control aphid populations.

Disturbing Ecosystem Relationships

Consider the impact that one new species may have on an ecosystem. Species within an ecosystem are engaged in many ecological relationships. They compete for resources, and they have symbiotic arrangements. All species are parts of food chains and food webs. Any direct interaction between two species affects not only these two species, but many other species as well. For example, when hawks prey on snakes, they reduce the population density of the snakes. This affects the mouse population, allowing it to increase. The larger mouse population could feed heavily on grass seeds, lowering the reproductive success for these plants. However, the most significant ecosystem disruptions often result from the introduction of a non-native invasive species or the loss of a species.

Figure 12 Garlic mustard disrupts nutrient cycling, making native plants less able to compete for resources.

One example of a non-native invasive species is the garlic mustard plant (*Allieria petiolata*), which is native to Europe and was introduced into North America in the early 1900s (**Figure 12**). It disperses quickly and widely and, once established, dominates the area. It has become established throughout southern Ontario and invades forest edges along roadsides and forest communities in floodplains. It seems to grow well in any medium (sand, loam, and clay soils), and it is virtually impossible to eradicate. Once established, it increases in density until it dominates the understorey. This interferes with the growth and survival of native species, since it competes with them for nutrients, space, moisture, and light.

Another invasive species is the rusty crayfish, which has damaged Ontario freshwater ecosystems. The rusty crayfish feeds on aquatic plants, invertebrates, and fish eggs, and is outcompeting native crayfish species. Its most serious damage results from the loss of aquatic plants, which are not only important food sources and habitats for many invertebrates and fish, but also help to reduce beach erosion caused by waves.

Another example of relationships in an ecosystem is the interaction of grey wolves and humans. The grey wolf was hunted to near extinction in the early part of the twentieth century in many parts of North America, including southern Ontario. The wolf is a top predator and kept the deer population under control. With few wolves left in southern Ontario, the white-tailed deer population increased dramatically. Urban encroachment on their habitat and reduced resources have pushed the deer population closer and closer to human populations, resulting in damage to agricultural crops.

The interactions between interdependent species can be subtle, but they are essential for maintaining healthy ecosystems. Human activities, such as the introduction of non-native species and habitat destruction, are upsetting the dynamic equilibrium in many ecosystems. Introduced non-native species are a major concern worldwide (**Figure 13**). They cause other species to become extinct, and they have a significant impact on species management. Habitat destruction is currently ranked as the primary cause of species extinction worldwide. Because all the species in an ecosystem are interdependent, a change in even one species can have a direct impact on the entire ecosystem.

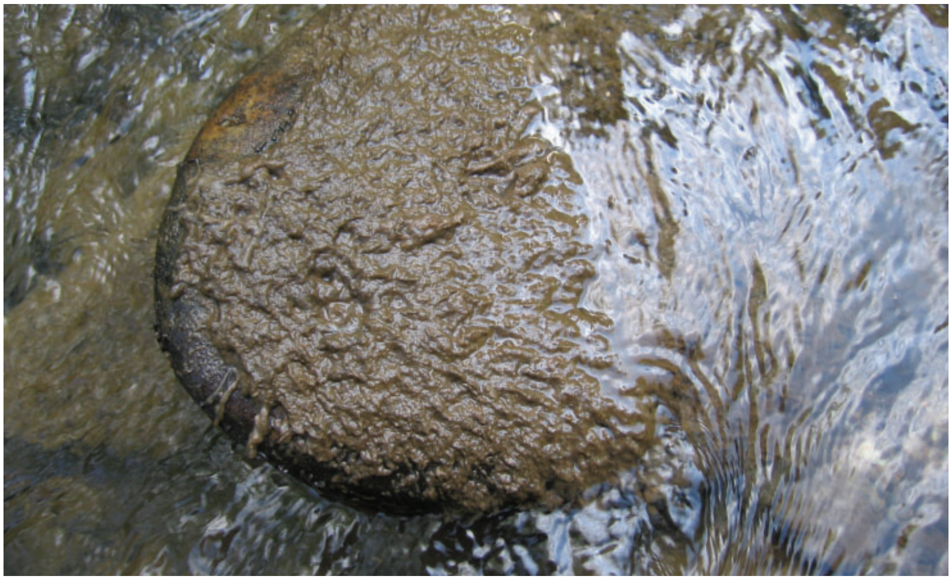


Figure 13 *Didymosphenia geminata*, or "rock snot," is a type of freshwater algae that is a global invasive species. It has spread from British Columbia all over the world, even to this river in New Zealand. The algae is yellowish brown and slimy. Although it does not threaten human health, it may disrupt food webs.

12.5 Review

Summary

- Many different kinds of interactions, which occur both among and between species, affect population growth.
- Predator-prey interactions are affected by many factors. Both the predator and the prey coevolve to enhance their survival.
- Interspecific interactions can be predatory, herbivorous, competitive, mutualistic, commensal, or parasitic.
- Competition among ecologically similar species is a factor that affects their population growth.
- Loss of a species, invasion of a non-native species, and human interference can disrupt the stability of an ecosystem.

Questions

1. Define "coevolution," and give an example of two organisms that have coevolved. Describe how both organisms have changed, and explain the benefits and drawbacks for each organism. K/U
2. Using the Internet, research the following pairs of organisms. Identify the type of population interaction. K/U T/I
   (a) clownfish and sea anemones
   (b) schistosomes and humans
   (c) blue whales and krill
   (d) two trees growing close together
   (e) white-tailed deer and foliage
   (f) killer whales and seals
   (g) cattle egrets and livestock
3. Explain how mimicry differs from camouflage. K/U T/I
4. Bears are generally classified in the carnivore order, but this may not always be the most accurate classification. Research the eating habits of the black bear, the grizzly bear, and the polar bear to find out the correct classification for each. List what each type of bear usually eats and what it may also eat under unusual circumstances. T/I C
5. Charles Krebs, a professor of zoology at the University of British Columbia, led a 10-year study of lynx and snowshoe hares in collaboration with 8 other scientists from 3 Canadian universities. Use the Internet to learn about his research project. Summarize his project and his conclusions. Include answers to the following questions:
   - What does Krebs feel are two of the world's most important ecological problems?
   - What is the fence effect, or Krebs effect? What factors have been proven not to explain the fence effect? T/I C
6. All octopuses can change colour and texture, but the mimic octopus, found in Southeast Asia, uses some unique defence mechanisms (**Figure 14**). Using the Internet or other sources, research this octopus. T/I
   (a) What specific defence mechanisms can this octopus use that other octopuses cannot?
   (b) What organisms can it mimic?

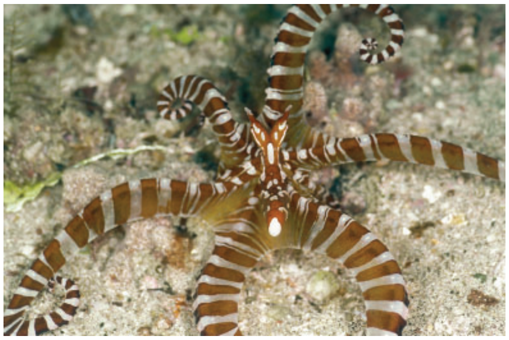


Figure 14

7. Using the Internet or other sources, select a plant or animal species from your area and consider its role and functions within its population and ecosystem. Include the following information in your description:
   - its role in its ecosystem
   - interspecific interactions that affect it
   - density-dependent/independent factors that may affect it
   - other population dynamics
   - the impact of human activities on its habitat
   - its conservation status
   - any changes/solutions that could improve its conservation status T/I

WEB LINK

CHAPTER 12 Investigations

Investigation 12.4.1 CONTROLLED EXPERIMENT

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Factors That Affect Populations

The survival of an organism depends on the physical conditions of its environment. The relationship between an organism and its environment is difficult to investigate over the short time span of a field study, but a controlled study can be done in a laboratory.

In this investigation, you will design a controlled experiment to determine one optimum environmental condition for the growth and survival of an organism of your choice.

Testable Question

Formulate a testable question based on the organism and variable that you decide to test. For example, here are two possible questions: What is the optimum level of salinity for the hatching of brine shrimp? What is the optimum amount of sunlight for the growth rate of seedlings?

Hypothesis

Formulate a hypothesis based on your testable question, after considering the options for your experimental design.

Variables

As you design your controlled experiment, carefully choose your independent and dependent variables. Decide which variables you will need to control.

Experimental Design

Choose an organism that can be easily cultured and is large enough to observe and count individually. The population does not need to reproduce, but you must be able to observe the death and/or birth of organisms. Possible organisms include brine shrimp (which you can hatch from eggs) and plants grown from seeds. Another possibility is yeast. You could culture a yeast population and count the number of cells under a microscope, but this would be more challenging. Do not use bacteria. Carefully consider how you will collect and record your data. Include any safety precautions you should take. Obtain your teacher's approval before proceeding.

Carefully consider all the safety hazards that could be involved in your experiment, and take all the necessary safety precautions.

Equipment and Materials

Make a complete list of materials that you will need, and confirm with your teacher that these materials are available.

Procedure

SKILLS HANDBOOK A1, A2.2

1. Decide on the population that you want to study.
2. Choose the factor that you will manipulate.
3. Prepare a set of experimental steps that will allow you to control all the variables, except the variable that you want to manipulate. Be clear about the precise variable that you want to manipulate (for example, light, temperature, or the concentration of a solution), and make sure that the location for your experiment does not interfere with this variable.
4. Devise a method for measuring and recording the response of your organism to the independent variable. What will you count and/or measure? How will you record your data (for example, in tables)? Will you graph your data? Determine how you will define "survival" in your experiment. At what point will you consider your experiment complete?
5. Obtain your teacher's approval for your experimental design. Then gather the equipment and materials you will need.
6. Conduct your experiment.
7. Record your observations in the appropriate format.

Analyze and Evaluate

SKILLS HANDBOOK A2.6, A3

(a) Analyze and evaluate your results. Present your findings in the form of an article that could be published in a scientific journal. This type of article includes the following sections:

Abstract, Introduction, Method, Results, and Discussion

Scientific journal articles are often peer reviewed within the scientific community before they are published. You may want to conduct your own peer review by having your lab partner review your article. T/I C

Apply and Extend

(b) Answer the following questions, based on the results of your experiment. T/I
  - (i) What aspects of your experiment could be changed to improve your study? Why?
  - (ii) What recommendations for further research would you make?
  - (iii) What other questions did your research suggest could be studied?

(c) There are arguments for and against the use of animals in scientific experiments. A
  - (i) Why are animals used in experiments?
  - (ii) What are the potential benefits of using animals in experiments?
  - (iii) What is the harm of using animals in experiments?
  - (iv) Are there any alternatives to using animals for research? What are they?

Investigation 12.5.1 OBSERVATIONAL STUDY

Investigating Predator-Prey Cycling

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Isle Royale is a remote island that is located in the northwest part of Lake Superior, approximately 30 km from the Canadian mainland. It has no roads, and no motorized vehicles are allowed. It is closed to tourists from September to May. During this time, the only human residents are researchers, making it an ideal living laboratory.

Isle Royale is home to a wolf population and a moose population that have been studied and researched since 1958. Neither species is native to the island. Moose swam across Lake Superior in the early 1900s and lived on the island for almost 50 years with no predators. A pair of wolves migrated to the island over a winter ice bridge in 1949, and the predator-prey relationship began. The populations of both animals have varied over the years. The moose (**Figure 1**) are affected by their predator, but also by the availability of food and the severity of the winters.

Figure 1 Isle Royale moose

The moose are an important food source for the wolves, but not their only food source. Wolves also feed on beavers and other small animals that live on the island (**Figure 2**).

Figure 2 Isle Royale wolves

Part A: Wolves and Moose

Purpose

To graph and analyze the data for the wolf and moose populations on Isle Royale, which wildlife biologists have collected over the last 50 years

Equipment and Materials

- graph paper and a pencil, or a computer or calculator with a spreadsheet/graphing program

Procedure

SKILLS HANDBOOK A2.4, A5.4

1. Obtain the moose and wolf population data online or from your teacher.
2. Using graph paper or a graphing program, plot both sets of data on the same axes. Use a different scale for each population.

Apply and Extend

(b) Answer the following questions, based on the results of your experiment. T/I
  (i) What aspects of your experiment could be changed to improve your study? Why?
  (ii) What recommendations for further research would you make?
  (iii) What other questions did your research suggest could be studied?

(c) There are arguments for and against the use of animals in scientific experiments. A
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Investigation 12.5.1 OBSERVATIONAL STUDY

Investigating Predator-Prey Cycling

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
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- Evaluating
- Communicating

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Figure 2 Isle Royale wolves

Part A: Wolves and Moose

Purpose

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Equipment and Materials

- graph paper and a pencil, or a computer or calculator with a spreadsheet/graphing program

Procedure

SKILLS HANDBOOK A2.4, A5.4

1. Obtain the moose and wolf population data online or from your teacher.
2. Using graph paper or a graphing program, plot both sets of data on the same axes. Use a different scale for each population.

Analyze and Evaluate

(a) Which population is larger: the prey or the predators? Account for this observation. T/I

(b) Do you notice any trends or patterns in the data you graphed? Describe them. T/I

(c) Biologists discovered that a deadly canine parvovirus had been introduced to the island when a visitor brought a dog. Based on your graph, when did the virus affect the wolf population? What happened to the moose population at this time?

(d) When did the wolf population peak? Was this associated with high moose numbers? T/I

(e) Describe at least one piece of evidence that suggests that the moose and wolf populations influence each other. T/I

(f) Explain how density-dependent and density-independent factors have affected both animal populations on Isle Royale. T/I

Apply and Extend

(g) When this study began, many researchers believed that the two species would eventually reach a population equilibrium (thought to be about 25 wolves to 1500 moose). This has not happened. In fact, the pattern tends to fluctuate unpredictably. Using the Internet, find other factors that the researchers believe are affecting the populations. 🌐 T/I

(h) How have the other species on Isle Royale been affected by the wolf-moose ecosystem? T/I

(i) Beavers benefit both the wolf and moose populations. Explain why. T/I A

Part B: Population Simulations

In this chapter, you have seen a number of mathematical equations and relationships that can be used to model population growth. Such models can be used not only to generate graphical data but also to run computer simulations. In this part of the investigation, you will do online research for a computer simulation of predator-prey relationships or interspecies competition. Then you will report on your findings to your peers.

Purpose

To research and use a computer simulation to model a predator-prey or interspecies competitive relationship

Equipment and Materials

- computer with Internet access

Procedure

3. Using the Internet, search for an online computer simulation of population dynamics, such as a predator-prey relationship or interspecific competition. 🌐
4. Run the simulation. Note which variables are being manipulated and which are being monitored and/or recorded.
5. Record any overall patterns that you notice, any changes that occur in the populations, and the final results of the simulation.

Analyze and Evaluate

(j) Describe the features of the simulation. T/I

(k) What variables were measured? T/I

(l) How did the simulation perform? Describe the results. T/I

(m) How valid do you think the simulation was? Was it an accurate measure of reality? T/I

(n) How could the simulation be improved? T/I

(o) Share the information about the simulation you used with your peers, and learn about their simulations. How are the simulations similar, and how are they different? T/I C

🌐 WEB LINK

CHAPTER 12 SUMMARY

Summary Questions

1. Create a study guide for this chapter based on the Key Concepts on page 582. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 582. Answer these questions again, using what you have learned in this chapter. Compare your latest answers with those that you wrote at the beginning of the chapter. Note how your answers have changed.

Vocabulary

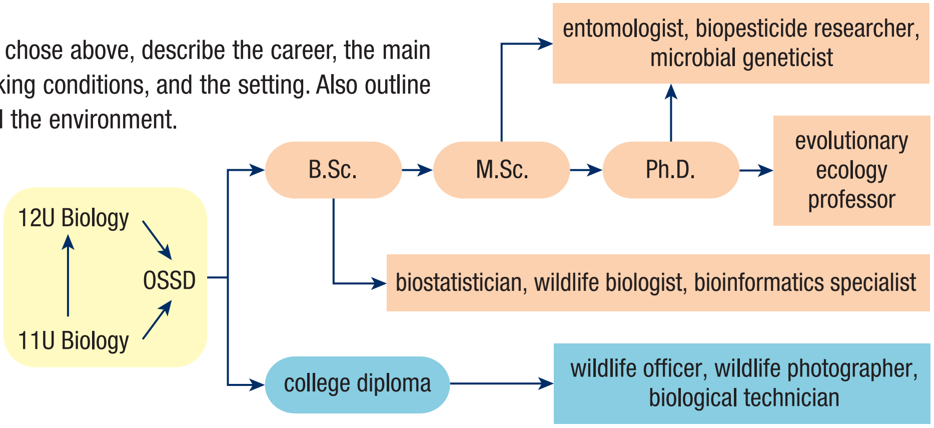
population ecology (p. 584)
geographic range (p. 584)
habitat (p. 584)
population size (N_t) (p. 585)
population density (D) (p. 585)
crude density (p. 585)
ecological density (p. 585)
dispersion (p. 586)
quadrat (p. 588)
mark-recapture method (p. 589)
demography (p. 593)
natality (p. 593)
mortality (p. 593)
immigration (p. 593)
emigration (p. 593)
life table (p. 593)
cohort (p. 593)
age-specific mortality (p. 594)
age-specific survivorship (p. 594)
survivorship curve (p. 595)
fecundity (p. 596)
generation time (p. 597)
sex ratio (p. 597)
population dynamics (p. 600)
exponential model of population growth (p. 600)
per capita growth rate (r) (p. 601)
zero population growth (ZPG) (p. 602)
carrying capacity (K) (p. 605)
logistic model of population growth (p. 605)
sigmoid curve (logistic) (p. 606)
limiting factor (p. 610)
density-dependent factor (p. 610)
density-independent factor (p. 610)
competition (p. 610)
interspecific competition (p. 610)
intraspecific competition (p. 610)
predation (p. 610)
Allee effect (p. 612)
minimum viable population size (p. 613)
coevolution (p. 616)
herbivory (p. 616)
mutualism (p. 616)
parasitism (p. 616)
commensalism (p. 616)
mimicry (p. 618)
interference competition (p. 621)
exploitative competition (p. 621)
fundamental niche (p. 622)
realized niche (p. 622)
resource partitioning (p. 622)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to natural population dynamics that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.


entomologist, biopesticide researcher, microbial geneticist
evolutionary ecology professor
B.Sc.
M.Sc.
Ph.D.
12U Biology
OSSD
11U Biology
biostatistician, wildlife biologist, bioinformatics specialist
college diploma
wildlife officer, wildlife photographer, biological technician

CAREER LINK

CHAPTER 12 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which term refers to the total area that is occupied by a population? (12.1) K/U
   (a) geographic boundary
   (b) geographic range
   (c) geographic density
   (d) geographic size
2. Which dispersion pattern do fish generally exhibit? (12.1) K/U
   (a) random dispersion
   (b) uniform dispersion
   (c) clumped dispersion
   (d) linear dispersion
3. How are population density and population dispersal different? (12.1) K/U
   (a) Population density measures the number of individuals in an area, not how they are grouped.
   (b) Population dispersal measures the number of individuals in an area, not how they are grouped.
   (c) Population density describes the way individuals are arranged in an area.
   (d) Population density can be calculated while population dispersal cannot.
4. Which of the following best describes the mortality rate of organisms following a type I survivorship curve? (12.2) K/U
   (a) fairly constant throughout life
   (b) high early in life
   (c) steadily decreasing throughout life
   (d) low in the early and middle years
5. Horseshoe crabs have a high fecundity. What does this mean? (12.2) K/U
   (a) They have a long lifespan.
   (b) They have a short lifespan.
   (c) They produce a large number of offspring.
   (d) They reproduce very few offspring.
6. Which kind of population growth does the exponential population model predict? (12.3) K/U
   (a) unlimited growth
   (b) zero population growth
   (c) slow growth that stabilizes
   (d) decrease in population
7. Which type of growth curve represents a population that has reached its carrying capacity? (12.3) K/U
   (a) J-shaped (c) S-shaped
   (b) U-shaped (d) straight
8. Which of the following is a density-dependent factor? (12.4) K/U
   (a) human activities
   (b) climate
   (c) pollution
   (d) Allee effect
9. Which term refers to a relationship between two different organisms that benefits both organisms? (12.5) K/U
   (a) predation
   (b) commensalism
   (c) mutualism
   (d) herbivory
10. Two male tigers compete for the right to mate with the same female. Which of the following best describes this type of competition? (12.5) K/U
   (a) intraspecific competition
   (b) interspecific competition
   (c) symbiotic competition
   (d) predation

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Crude density refers to the number of individuals per unit area that is actually used. (12.1) K/U
12. The quadrat method of sampling is most effective for estimating the population size and density of small or immobile organisms. (12.1) K/U
13. A life table summarizes the demographic characteristics of a population. (12.2) K/U
14. Exponential population growth can occur only if there are limited resources. (12.3) K/U
15. Most natural populations show logistic population growth. (12.3) K/U
16. The carrying capacity of a population does not depend on the environment. (12.4) K/U
17. The Allee effect occurs when populations become too large and cannot survive. (12.4) K/U
18. Mimicry is an example of coevolution. (12.5) K/U
19. In a parasitic relationship, one organism benefits and the other organism is not affected. (12.5) K/U
20. Predator-prey interactions may contribute to the density-independent regulation of both populations. (12.5) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. Which term refers to all the individuals of a single species that live together in the same place at the same time? (12.1) K/U
   (a) community
   (b) genus
   (c) population
   (d) ecosystem
2. Which dispersion pattern does territorial behaviour produce? (12.1) K/U
   (a) random dispersion
   (b) clumped dispersion
   (c) uniform dispersion
   (d) linear dispersion
3. A population of 1000 individuals experiences 452 births and 380 deaths in one year. What is the age-specific survivorship for this population? (12.2) K/U T/I
   (a) 0.62
   (b) 0.062
   (c) 0.38
   (d) 0.038
4. Which of the following describes a type II survivorship curve? (12.2) K/U
   (a) Most individuals die during their reproductive years.
   (b) Most individuals die at a constant rate throughout time.
   (c) Most individuals die of old age.
   (d) Most individuals die early in life.
5. During exponential growth, what always happens to a population? (12.3) K/U
   (a) It grows by thousands of individuals.
   (b) It grows at its maximum per capita rate.
   (c) It quickly reaches its carrying capacity.
   (d) It loses some individuals to emigration.
6. Approximately how many years does it take for a population with an annual growth rate of 0.3 % to double? (12.3) K/U
   (a) 15 years
   (b) 30 years
   (c) 160 years
   (d) 230 years
7. Which statement about density-dependent factors is correct? (12.4) K/U
   (a) They cause the exponential growth of a population.
   (b) They have greater impact as population density increases.
   (c) They include floods, fires, and landslides.
   (d) They include temperature extremes.
8. Which example might reflect the density-independent regulation of a population? (12.4) K/U
   (a) An exterminator sprays a pesticide to eliminate termites in a home.
   (b) A lack of food causes starvation in a deer population.
   (c) The mosquitoes in a city disappear after entomologists release thousands of dragonfly larvae in the spring.
   (d) White-nose syndrome affects bats in Ontario.
9. Which statement about intraspecific competition is most accurate? (12.4) K/U
   (a) It increases with resource partitioning.
   (b) It involves interactions between individuals of different species.
   (c) Researchers can easily demonstrate that it occurs in a natural environment.
   (d) It is strongest between organisms that occupy different ecological niches.
10. Zebras' black and white lines allow them to stay together and make it hard for prey, such as a lion, to see any one zebra because they look like a blurry shape. What is this defensive strategy called? (12.5) K/U
    (a) camouflage
    (b) mimicry
    (c) herbivory
    (d) predation

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

11. Random dispersion patterns appear to be rare in nature. (12.1) K/U
12. The long-term effects of studying and monitoring animal populations are well understood by scientists. (12.1) K/U
13. population change
    = (births + immigration) – (deaths + emigration)
    (12.2) K/U
14. Demography is the study of population change. (12.2) K/U

15. Doubling time is the average time between the birth of an organism and the birth of its offspring. (12.2) K/U
16. Most populations undergo exponential growth for most of their lifespan. (12.3) K/U
17. The logistic growth model attempts to describe the real-world relationship between population growth and carrying capacity. (12.3) K/U
18. The adaptation of carnivorous predation in plants allows them to avoid intraspecific competition. (12.4) K/U
19. A tree species that grows taller than other tree species in a dense forest is an example of intraspecific competition. (12.4) K/U
20. Resource partitioning is a way for two different species to share the same habitat. (12.5) K/U
21. Parasitism is a form of commensalism in which the host is usually not killed. (12.5) K/U

Match each term on the left with the most appropriate description on the right.

22. (a) herbivory
    (b) parasitism
    (c) predation
    (d) commensalism
    (e) competition
    (f) mutualism

(i) A tapeworm lives in the gut of an animal and gets its food by absorbing the digested food. The host does not die, but its health could suffer.
(ii) Certain types of silverfish follow army ants on their raids for food. The silverfish do not take part in the raids, but they share the food.
(iii) An insect feeds on the nectar and pollen of flowers. The pollen attaches to its body. The insect spreads the pollen to other plants, enabling these plants to complete the fertilization process.
(iv) Two male deer battle during mating season.
(v) Panda bears feed on bamboo, and koala bears feed on eucalyptus trees.
(vi) An Indian python swallows a deer whole. The python benefits, while the deer clearly does not. (12.5) K/U

Write a short answer to each question.

23. Using an example, explain the difference between crude density and ecological density. (12.1) K/U
24. Why is it important for scientists to track and monitor populations of species in Canada? (12.1) K/U
25. Explain how life tables and survivorship curves can be useful to biologists who are monitoring populations of species. (12.2) K/U A
26. (a) Describe natality, mortality, immigration, and emigration.
    (b) How do these factors affect population size and dynamics? (12.2, 12.3) K/U
27. The smallest flowering plant on Earth, duckweed (**Figure 1**), has a growth rate (*r*) of 0.556 per day. Calculate the doubling time of duckweed. (12.3) K/U

Figure 1

28. The logistic model of population growth predicts an S-shaped curve for population size over time. Which area of the curve represents the fastest growth? (12.3) K/U
29. (a) What is minimum viable population size?
    (b) Why do scientists use minimum viable population size? (12.4) K/U
30. Biotic factors that affect populations tend to be density-dependent, while abiotic factors that affect populations tend to be density-independent. Explain why, using examples. (12.4) K/U
31. Compare and contrast interspecific competition and intraspecific competition. (12.5) K/U
32. Describe three defence mechanisms that organisms use to avoid becoming prey, and give an example of each. (12.5) K/U
33. Humans are involved in several types of symbiotic relationships. Choose one type, and describe it using an example. (12.5) K/U A

Understanding

34. (a) Balsam Lake Provincial Park covers an area of 448 ha. Calculate the crude density of blue jays in the park if 127 blue jays were counted (**Figure 2**).
    (b) What parts and proportion of the park might not be used by the blue jays? Based on your answer to this question, calculate the ecological density of the blue jays. (12.1) K/U T/I

Figure 2

35. Researchers from the Freshwater Institute are studying fish communities in Lake Winnipeg, which has an area of 2 375 000 ha. They caught and tagged 172 rainbow smelt in the top 30 % of the lake. Five days later, they recaptured 162 fish in the same area and found that 18 were tagged. (12.1) K/U T/I
    (a) Estimate the population size.
    (b) Rainbow smelt are a newly introduced species and are not native to Lake Winnipeg. They occupy the same areas of the lake as a native yellow perch species, and they tend to be more aggressive. Suggest two limiting factors for yellow perch that are illustrated by this situation. Decide whether each limiting factor is density-dependent or density-independent.
36. What is the common pattern of generation time among bacteria, protists, plants, and animals? (12.2) K/U
37. Suppose that you have captured, marked, and released 10 rabbits in a neighbourhood park. You recapture 20 rabbits 10 days later and find that 4 are marked. You estimate that the rabbit population in the park is 50 rabbits, based on your percentage sample. Suggest two ways that your estimate could be biased. Explain your reasoning. (12.1) K/U T/I
38. How can life tables help you understand the demography of a population? (12.2) K/U
39. What is age-specific fecundity? (12.2) K/U
40. What does it mean when $r < 0$, $r > 0$, or $r = 0$? (12.3) K/U
41. Define the terms in the equation $\frac{dN}{dt} = (b - d)N$. (12.3) K/U
42. During the summer, a population of aphids on a bush exhibits exponential growth. The initial population on the bush is 37, and the rate of increase is 0.281 per day. What is the growth rate of the population? (12.3) K/U
43. A hypothetical population has a per capita growth rate of 2.5 % per year. Determine the approximate time it will take for the population to double in size. (12.3) K/U
44. What is the difference between a generalist and a specialist species? (12.5) K/U
45. Why would completely removing a predator from a community not be a good idea? (12.5) K/U

Analysis and Application

46. The exploitation of whales by the whaling industry has led to serious declines in many of the world's populations of whales. Use the estimated whale population data in **Table 1** to answer the following questions. (12.1) K/U T/I C

Table 1 Whale Population Data

Species of whale	Population before hunting	Present population
northern right whale	10 000	300
blue whale	228 000	11 000
sei whale	256 000	54 000
humpback whale	115 000	2 500
bowhead whale	30 000	8 000
grey whale	20 000	17 000

    (a) Graph the data using graphing or spreadsheet software and the most appropriate type of graph to clearly convey the information represented.
    (b) Other than whale hunting, what other threats could exist for whale populations?
    (c) When the status of a species is a concern, population viability studies are often done. Based on the data, which species may be a concern?
    (d) Which whale population does not follow the trend? Suggest reasons for the difference.
    (e) Based on what you have learned in this chapter, how do you think scientists track and monitor whale populations?

47. Why might population numbers fluctuate or oscillate instead of maintaining a steady level? (12.3) K/U T/I
48. At the beginning of a year, there were 1923 painted turtles in a population. Over the year, 343 painted turtles were born, 176 died, 72 immigrated from other areas, and 12 emigrated. (12.3) K/U T/I
    (a) Determine the percentage population change of the painted turtle population.
    (b) Do you think this information is enough to determine whether or not the growth rate of the population is a cause for concern? Explain your reasoning.
    (c) While an accurate count of the turtle population is essential, what other data are important for developing a good conservation plan?
49. Although logistic growth models are realistic for most populations, very few populations actually produce the sigmoid curve. Instead, most populations tend to fluctuate around the carrying capacity. Choose a limiting factor, and show how it would cause this fluctuation. (12.3) K/U T/I
50. A population of pet mice in a cage stops increasing even though there is enough food to support a larger population. What type of population regulation is occurring? Explain your choice. (12.4) T/I
51. Scientists can determine the health of an ecosystem by studying its biodiversity. They can consider the number of different species in the ecosystem, determine the populations of several species, or look specifically at one or more indicator species. Frogs are considered to be an indicator species for the quality of wetland ecosystems. (12.4, 12.5) K/U T/I
    (a) How can natural environmental factors affect frog populations?
    (b) What human factors can affect frog populations in the wild?
    (c) Visual surveys are often used to collect population data for frogs. Would this kind of survey give accurate information about all the individuals in a wild population? Why or why not?
    (d) Would long-term or short-term population data give you a more accurate idea of the change in population size? Explain your answer.
    (e) Late-summer populations of frogs tend to be larger than spring populations. Why do you think this is?
52. How does competition differ from parasitism and predation? (12.5) K/U
53. Write a story about how one or more limiting factors affect a particular plant or animal in an ecosystem, from the perspective of this plant or animal. (12.4, 12.5) C A
54. Habitat loss is one threat that is facing native birds in North America, but not how you might expect. Birds must contend with predatory feral and domestic cats. According to estimates from some conservationists, feral cats and domestic cats that are allowed to roam outdoors kill around half a billion birds each year in North America alone. Except in North Africa, where domestic cats evolved, they are not a natural part of the ecosystem. Birds do not have sufficient natural defences to protect themselves and their young against feral and domestic cats. (12.5) K/U T/I C
    (a) Based on what you have learned about invasive species and population balance in ecosystems, what concerns might you have about this hyperpredation situation?
    (b) What possible solutions could you suggest?
    (c) Are there any downsides to these solutions?
    (d) Create a poster or brochure that encourages the general public to be aware of this situation and ways they can help.

Evaluation

55. The white shark is the most often depicted and most easily recognized species of shark. However, relatively little is known about the natural history, range, population structure, and reproductive biology of the white shark. Since 2000, pop-up archival satellite tags (PATs) have been used to study white shark migration and movements, and to infer behavioural patterns along migration routes. PATs are designed to record pressure, temperature, and light-level data when attached to marine animals. From pressure data, an animal's depth can be recorded, since pressure increases with depth. PATs can be pre-programmed to pop off after a pre-designated length of time. After being released, they float to the surface and uplink with the Argos satellite system, which downloads archived information. Use your knowledge of population monitoring and tracking to answer the following questions. (12.1) T/I A
    (a) Who benefits from the information obtained through this research?
    (b) Should this research be paid for using taxpayers' money, or should it be privately funded? Explain your answer.
    (c) Do you think the benefits justify the costs? Explain.
    (d) Rank the importance or priority of this research on a scale of 1 to 10 (10 being a very high priority). Explain why you ranked it the way you did.

56. Using the survivorship curve of the unidentified species in **Figure 3**, answer the following questions. (12.2) K/U T/I

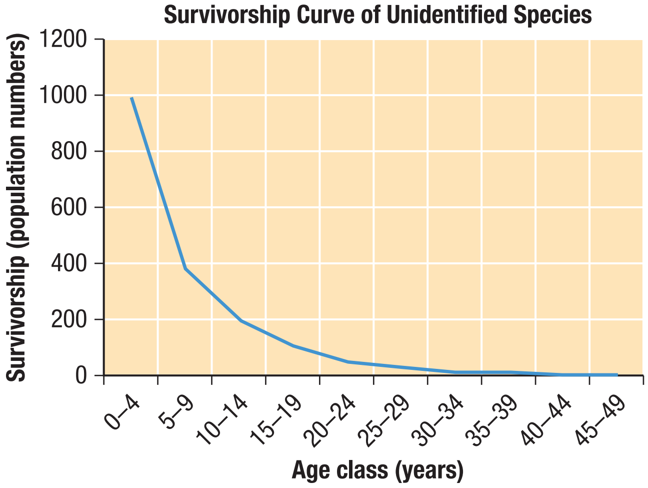


Figure 3

(a) What does the shape of the curve indicate about the mortality and age of this species?
(b) Based on Figure 3, would the population likely experience exponential growth? Why or why not?
(c) Based on your understanding of survivorship curves, what type of species is this likely to be? Could it be human?

57. Geometric and exponential growth models are not realistic, since actual populations do not show geometric or exponential growth patterns. Do you agree or disagree? Explain why. (12.3) T/I

58. Once zebra mussels arrived, there was no affordable way to get rid of them. They posed a serious threat not only to boats and structures on the water but also to native species of mussels. Once adult mussels laid eggs, the species spread. Zebra mussels have been a great concern for many years. However, despite a lack of human intervention, zebra mussel populations have been decreasing in many once-infested waterways. (12.5) T/I A

(a) Based on what you have learned about population density, suggest possible environmental reasons that may be curbing the zebra mussel population.
(b) Does this natural decrease in the zebra mussel population mean that we should be less concerned about zebra mussels as an invasive species? Explain.
(c) One legal definition of an invasive species is "an alien species whose introduction does or is likely to cause economic or environmental harm or harm to human health." Is it possible that humans are an invasive species? Explain your reasoning.

59. "It can be argued that predation has a positive effect on the prey species." Provide two reasons that support this statement. (12.5) K/U T/I

60. Scientists have estimated that, under ideal conditions, one bacterium could produce enough offspring to cover Earth with a layer 1 m deep. Explain why this has not happened. (12.3, 12.4, 12.5) T/I

Reflect on Your Learning

61. Because of the increasing number of accidents between moose and vehicles on the highways of Newfoundland and Labrador, some people are calling on the provincial government to cull the moose population. They are also asking the government to build fences along highways in areas where moose frequently cross. Other people, however, feel that more prudent driving and a reduction in highway speeds during the times of day when moose are most active will solve the problem. Write a letter to the provincial government of Newfoundland and Labrador, voicing your opinion about what should be done and explaining why you hold this opinion. T/I C

62. With the possible exception of a few very common tropical fish species, it is not a good idea to turn a wild animal into a pet. Based on what you have learned in this chapter, do you think you should "accessorize your life with wildlife"? Explain your thinking. T/I A

63. Do you think that urban sprawl and development are affecting the biodiversity of plants and animals in your community? Explain your reasoning with examples. T/I A

64. Should animal populations be managed and controlled through human activities, such as culling or hunting? Defend your position. T/I C

Research

WEB LINK

65. Biological control of pests relies on predation, parasitism, herbivory, and other natural mechanisms. Many Canadian cities have recently started to control mosquito populations through biological larvicides, instead of traditional chemical pesticides and adult control programs. Evaluate the pros and cons of biological pest controls. T/I A

(a) What biological controls can be used for mosquitoes?
(b) How do these biological controls work?
(c) What is the main advantage of using biological pest controls?
(d) What could be a possible downside to biological pest controls?

66. When studying polar bears (**Figure 4**), scientists generally use either the mark-recapture method or another common sampling technique called the line-transect method. Using the Internet or other sources, research the line-transect method and answer the following questions. T/I A
   (a) What is the line-transect method?
   (b) What assumptions are made when using the line-transect method?
   (c) Why would the line-transect method be used instead of the mark-recapture method when studying polar bears?
   (d) When would the mark-recapture method be a more useful sampling technique? What additional information does it provide?

Figure 4

67. How can you help to protect the environment from invasive species and thus sustain your community for generations to come? Suppose that you are working as a student researcher for the Government of Canada during the summer. You have been asked to select an invasive species that is currently found in Canada and write a report. Use the Internet or other sources to gather information. Your report should include the following information:
   - potential negative impact of the species
   - evidence of any interaction of the invasive species with native species
   - detailed description of any economic, social, or environmental effects
   - explanation of how the invasive species was introduced into the country and how it spreads
   - identification and explanation of any existing federal legislation regarding the species
   - recommendations or suggestions that the general public may follow to help prevent or stop the spread of the species T/I C A

68. In 1937, researchers at the University of Toronto began studying the migration paths of monarch butterflies. In 1975, they finally discovered the wintering locations of the two migratory populations of monarchs. The western population overwinters along the California Coast, and the eastern population overwinters in Mexico (and along the Gulf Coast in some years). A new group of volunteers in central California recently started an organization called Monarch Alert. They are tracking the spring movements of the western population, from San Luis Obispo County north to Marin County. Local groups in communities along the coast of California, where the monarchs spend the winter, are joining together to help protect habitats and learn more about these butterflies. There are also groups that monitor the eastern population of monarchs in North America. Use the Internet to explore the continuing work of the people who monitor these migration paths. Use the information you gather to answer the following questions. T/I
   (a) What is the Monarch Alert Project?
   (b) How are tracking tags placed on the butterflies? What are people asked to do if they spot a tagged butterfly (**Figure 5**)?
   (c) What are the goals of the project?
   (d) What do the researchers believe is changing and thus requires further study?
   (e) Many other organizations are also involved in monitoring and studying monarch butterflies. Find one organization that interests you, and explain its involvement in the project.

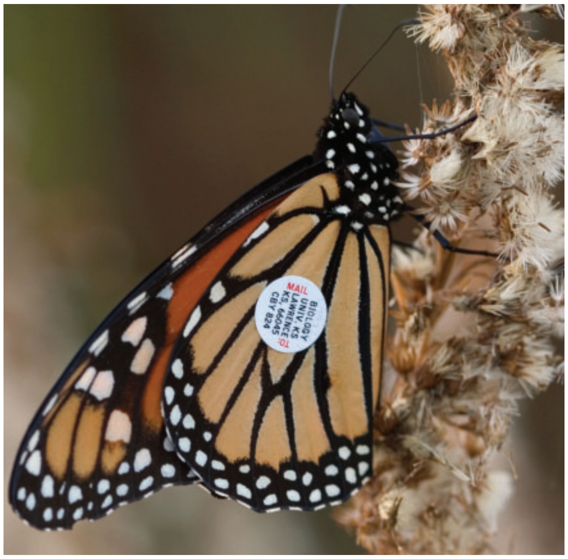


Figure 5

CHAPTER

13 Human Population Dynamics

KEY CONCEPTS

After completing this chapter you will be able to

- describe how advances in agriculture, technology, science, and medicine have helped shape human population growth
- understand that human activities have an associated ecological cost
- explain the ecological cost of human activities in terms of our ecological footprint
- understand that sustainable practices are necessary to feed, house, and provide a reasonable quality of life for an expanding population
- describe how individuals and countries are trying to minimize their own environmental impact while enhancing global sustainability

What Are the Limits to Human Population Growth?

About 2000 years ago, the world population was approximately 300 million people. By the end of 2011, it had increased to 7 billion people. According to estimates, by 2050, the world population will have increased to 9 billion people. Every day, approximately 350 000 people will be born and more than 150 000 will die. Much of this growth will take place in developing countries, where the demand for essential resources already outstrips the supply.

World population growth remained relatively stable until the beginning of the first millennium of the Common Era, when the human population began to grow at an exponential rate. The population growth in the last century has been astounding. After 1950, the population doubled in less than 40 years—a doubling period that is shorter than an average human's lifespan. Historically, population surges have been tied to cultural innovations and changes in the environment. The period of agricultural, manufacturing, mining, transportation, and technological development between the eighteenth and nineteenth centuries led to a surge in population growth. The nineteenth century also saw the introduction of sanitation, preventative medicine, and the use of antibiotics. These innovations started a downward trend in the mortality rate in most countries. The economic effects of the decreased mortality rate have led, over time, to a decreased birth rate in most developed countries. However, the high population growth rate in developing countries has continued.

Humans are an intelligent and successful species. Our innovations have provided better living conditions for much of the human population, but they have come with an ecological cost. Our ecological footprint is a measure of our demand on Earth's ecosystems, compared with Earth's ecological capacity to regenerate. Earth does not have an unlimited carrying capacity. We are currently using ecological resources faster than they can be renewed. Sustainable practices are necessary to feed, house, and provide a reasonable quality of life for an expanding human population. Canada and other countries must develop policies and technologies to minimize their own environmental impact while enhancing global sustainability.

STARTING **POINTS**

Answer the following questions using your current knowledge. You will have a chance to revisit these questions later, applying concepts and skills from the chapter.

1. Why have humans been so successful as a species? Give some examples.
2. What events in recent human history have significantly changed how humans use natural resources?
3. Brainstorm a list of factors that might limit the size of the human population in Canada. How might these factors differ from factors in other parts of the world?

Mini Investigation

World Population Clock

Skills: Questioning, Predicting, Analyzing

SKILLS HANDBOOK A2.1

Many factors influence the speed at which the human population grows. As you just read, the number of births per day is approximately 350 000, and the number of deaths per day is approximately 150 000. In this investigation, you will examine the pace of human population growth and consider the primary factors that influence birth and death rates.

Equipment and Materials: calculator

1. Calculate the change in the human population per week, per month, and per year.
2. Assuming that the current population is 7 billion, determine the yearly percentage change in the population.

A. The human population growth rate is currently slowing down. Do you think the birth rate is decreasing, the death rate is increasing, or both? T/I

B. What factors might be contributing to the slowing population growth rate? T/I

C. In some parts of the world, the human population is not growing. How do you think this affects the overall world population growth? T/I

D. There are two types of population density. Crude density measures the number of individuals of the same species within an area. Ecological density measures the number of individuals within an area that is actually used by the population. How do these two concepts affect how we think about human population growth? T/I

13.1 Human Population: Past and Present

The current human population is approximately 7 billion, vastly larger than the few thousand people who lived on Earth 100 000 years ago. How did the human population achieve this astounding growth? Unlike other species, humans have developed the capacity to expand into habitats and climate zones that were once uninhabited and increase the carrying capacity of the environment. We have removed or reduced many limiting factors that once regulated population growth. However, our planet's natural resources are stressed. We must learn to manage population growth in a sustainable way, which will allow all the people on Earth access to the resources needed for survival and a satisfactory quality of life.

The ever-growing population is not evenly distributed over the Earth's surface. Some areas continue to grow and increase in density, while others stabilize or even decline (**Figure 1**). In this chapter, we will examine the impact that the increasing human population is having on the natural environment, and what we should be doing to minimize it. Our impact is often measured as an **ecological footprint**, which is a measure of the water and land resources required and pollution created to meet our demands.

ecological footprint the impact imposed on the environment by the demand for natural resources

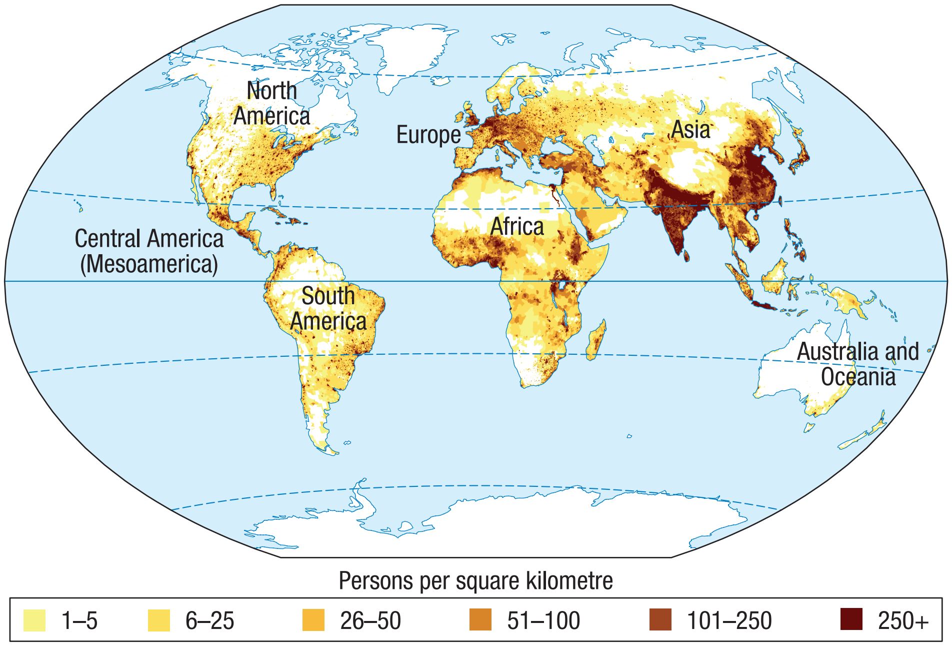


Figure 1 This map shows the distribution of the human population.

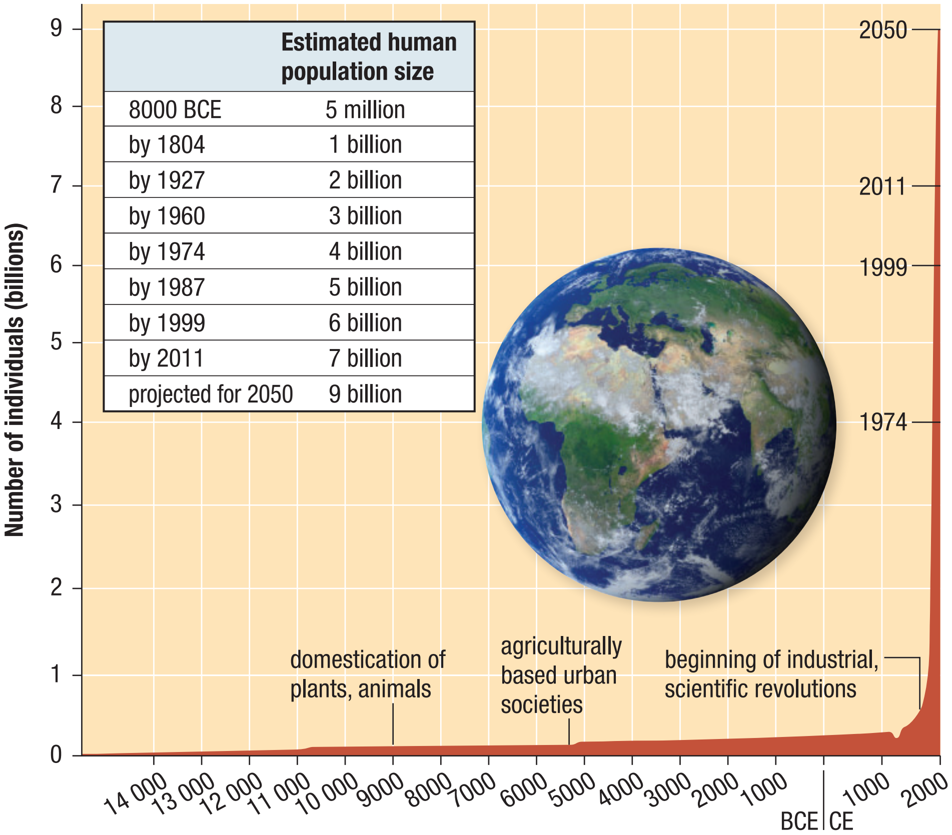
A Brief History of Human Population Growth

For most of human history, the world population grew slowly in response to density-dependent environmental factors, such as availability of food, water, and shelter, that limited resources. Over the past two centuries, however, the world population has grown exponentially. Demographers (scientists who study demography, or human populations) have identified four ways that humans have avoided the effects of density-dependent regulating factors. CAREER LINK

First, we have expanded our geographic range, alleviating competition for space. Our early ancestors lived in tropical and subtropical grasslands. By 40 000 years ago, however, they had dispersed through much of the world. They were able to do this because they could overcome limiting factors in their environment by making fires, building shelters, making clothing and tools, and planning community hunts. Language fostered communication of complex ideas, allowing vital survival skills to be passed down through generations and spread from one population to another.

Second, beginning about 11 000 years ago, the carrying capacity of many areas increased due to a shift from hunting and gathering to agriculture. Our ancestors cultivated wild grasses and other plants, diverted water to irrigate crops, and used domesticated animals for food and labour. Such innovations increased food supplies, thus increasing both the carrying capacity and the pace of population growth.

Third, in the mid-eighteenth century, people learned how to harness the energy in fossil fuels. This marked the beginning of industrialization in Western Europe and North America (**Figure 2**). In industrialized countries, food supplies and the carrying capacity rose again by the twentieth century, largely through the use of synthetic fertilizers, pesticides, and fast transportation and food distribution.



	Estimated human population size
8000 BCE	5 million
by 1804	1 billion
by 1927	2 billion
by 1960	3 billion
by 1974	4 billion
by 1987	5 billion
by 1999	6 billion
by 2011	7 billion
projected for 2050	9 billion

Figure 2 The world population grew slowly until 200 years ago, when it began to increase sharply. The dip in the mid-1300s represents the death of 60 million Asians and Europeans from the bubonic plague. The table shows how long it took for the human population to increase by each billion people.

Fourth, advances in public health reduced the effects of critical population-limiting factors, such as malnutrition, contagious diseases, and poor hygiene. Some of these advances were made hundreds, or even thousands, of years ago. In Rome, for example, the population was about 1 million people by 2 CE. People thrived due to excellent infrastructure for importing and distributing food, providing fresh water, and dealing with human waste. Over the past 200 years, advances in technology and social services have led to rapid population growth. The advent of modern plumbing and sewage treatment, improvements in food handling and processing, as well as advances in medicine, have reduced death rates and lengthened lifespans.

Domestication of Plants and Animals

Approximately 10 000 to 12 000 years ago, people began planting seeds to grow food. No one knows exactly when this happened, but evidence suggests that the idea of cultivating crops developed slowly over thousands of years. What we do know is that the advent of agriculture dramatically changed the course of human existence.

Many of the same foods that we eat today were among the first to be farmed by our early ancestors (**Table 1**, next page). For example, wheat and oats were planted in Asia about 10 500 years ago. Corn (or maize) was likely first cultivated in the region that is now Mexico about 10 000 years ago. Rice, a staple of many diets today, was first farmed about 9000 years ago.

Table 1 Approximate Times and Locations of the Domestication of Important Plants and Animals

Area	Plants	Animals	Earliest known date of domestication
Southwest Asia	wheat, pea, and olive	sheep, goat, and cattle	8500–6000 BCE
Mesoamerica	corn, beans, and squash	turkey	8000–3500 BCE
China	rice and millet	pig, silkworm, and water buffalo	7500–4000 BCE
New Guinea	sugar cane and banana	none	7000 BCE
Sahel	sorghum and African rice	guinea fowl	5000 BCE
Andes and Amazonia	potato and cassava	llama	3500 BCE
Ukraine and Central Asia	none	horse	3000 BCE
tropical West Africa	African yams and oil palm	none	300 BCE

Raising livestock also changed human existence. Livestock provided people who were living in areas that were not good for producing crops (such as rocky or steep ground) with another source of food. Animals in these areas converted the native inedible plants into a food that could be eaten. Sheep, goats, and pigs were among the first to be raised by humans in Asia, starting around 10 000 years ago. Cattle soon followed, about 8000 years ago, in Southwest Asia, India, and possibly North Africa. Horses were harnessed for work, and also used for milk and meat, approximately 5000 years ago in Eastern Europe. Location and indigenous species played a significant role in the development of agricultural practices. Some regions, for example, had no large animals that were suitable for domesticating. Other regions had soil that could not support crops, so people were limited by the plants and animals around them.

With the domestication of plants and animals, populations were transformed from small mobile groups of hunter-gatherers into societies in permanent villages and towns. People in these permanent communities were able to modify their natural environment through irrigation and specialized crop cultivation. This led to the development of food storage practices and technologies, which resulted in surplus food production. Populations with large agricultural food surpluses were able to spread out around the world, taking with them their domesticated animals, plants, and other technological advancements. For example, European settlers brought many plants and animals, including wheat, barley, horses, cattle, and pigs, to North America. Not everything that European settlers brought with them was beneficial to the Indigenous peoples. European diseases decimated Aboriginal populations. Guns provided the Europeans with immediate military superiority, and their centralized form of government, so different from the Aboriginal form of government, promoted institutions that controlled and took the place of the sustainable Aboriginal ways of life.

People and Pathogens: Diseases on the Rise

The establishment of large permanent communities had an unanticipated effect. Increased population density made it easier for disease-carrying organisms to spread. A **pathogen** (a disease-causing agent, such as a virus, bacterium, protozoan, or fungus) can cause an **epidemic** (a disease that spreads rapidly through a population) if a community lacks the proper resistance to the pathogen. Most pathogens can only be sustained and evolve in high-density populations. Measles, for example, will persist in a population of about 500 000 people or more, but it will soon die out in a smaller population.

pathogen a disease-causing agent, such as a microbe or fungus

epidemic the spread of a disease beyond a very local population

The domestication of animals contributed to the spread of pathogens, since diseases jumped from these animals to human populations. Early human diseases arose in regions of the world where human populations were dense and where animal domestication was widespread. China, Southeast Asia, North Africa, and Europe experienced some of the worst epidemics in human history. However, it was in these regions of the world that humans started to develop resistance. Resistance reduced the impact of a disease on the populations that had been afflicted with it. Unfortunately, when these populations moved around the world and interacted with previously unexposed populations, they inadvertently infected hundreds of thousands of others. The best-known example of the spread of a disease from animals to humans is the Black Death, also known as the bubonic plague, which was caused by the bacterium *Yersinia pestis*. It caused millions of deaths worldwide when it spread from China to Europe in the fourteenth century. **Table 2** lists a few human diseases that likely originated in animals.

When European explorers reached the shores of the Americas, they exposed the Aboriginal peoples to "new" diseases. These diseases from Europe spread rapidly and were acute. They had evolved to move rapidly through large populations (first large herding animal populations and then large human populations). Because the Aboriginal peoples had never been exposed to these diseases, they had no resistance. Epidemics devastated their populations. For example, a major smallpox epidemic in 1837 reduced the Mandan First Nation population in the Dakotas from 2000 to fewer than 40 individuals in a few weeks. The Aboriginal peoples had serious diseases that were contracted by the Europeans, but these diseases were not adapted to move through large populations. Therefore, they were less devastating to the European populations as a whole.

Smallpox, whooping cough, and other diseases brought tragedy to many communities, and local populations suffered great losses. Yet, on a global scale the human population was steadily increasing. An estimated 300 million people inhabited the world at the beginning of the Common Era. As agricultural, industrial, and technological practices developed, the human population grew to approximately 500 million by the year 1650. However, industrialization imposed pressures on the environment due to the increased extraction and consumption of raw materials, pollution emissions, and demand for energy.

Table 2 Probable Animal Origins of Human Diseases

Disease	Animal origin
smallpox	cattle and other livestock
influenza	pigs and ducks
tuberculosis	cattle
measles	cattle
HIV (human immunodeficiency virus)	chimpanzees
West Nile virus	birds
SARS (severe acute respiratory syndrome)	bats and civets

The Influence of Science, Technology, and Medicine

Science and technology have been influential throughout much of human history, in terms of both their social and environmental impacts (**Table 3**). All of these innovations affected the environment, either directly by increasing pollution or indirectly by leading to an increase in the human population. By the end of the seventeenth century, science had become an established empirical body of knowledge. In biology, the cell theory and the germ theory of disease provided the foundation for modern medicine. The major changes in agriculture, manufacturing, mining, transportation, and technology of the **Industrial Revolution** in the eighteenth century had a profound effect on the socioeconomic and cultural conditions of the times. The steam engine and later the internal combustion engine provided unrivalled sources of power for industry and agriculture.

Industrial Revolution a period of great technological advancement from the 1800s to 1900s, during which machines were developed

Table 3 Impacts of Scientific and Technological Breakthroughs

Breakthrough	Social impact	Environmental impact
vaccines	decreased death and disfigurement from viral diseases	increased human population and demand for resources
antibiotics	decreased incidence of and death from bacterial diseases	bacterial resistance due to overuse
water treatment	decreased spread of water-borne diseases; increased access to drinking water	overuse of water resources
steam engine and internal combustion engine	increased productivity, transportation, and manufacturing	pollution, habitat destruction, and climate change
fertilizers and pesticides	increased crop yields	overuse of land, pollution of water supplies and soil, risks to human health and wildlife

Meanwhile, advances in chemistry led to the production of countless new compounds, such as synthetic fertilizers, which enabled farmers to produce more food. The most dramatic and immediate effect on human populations resulted from the significant increase in food supply and the reduction in labour needs. Populations became increasingly urbanized as tractors and trains replaced teams of horses.

vaccine an injection of a dead or inactivated virus to spur an immune response

As well, advances in public health improved the chances for survival. Major breakthroughs included improving sanitation and waste removal, improving the quality of the water supply and expanding access to clean water, researching the causes and understanding the transmission of infectious diseases, and developing antibiotics and **vaccines** (injections of inactive or dead viruses that create resistance). Safer workplaces, limits on child labour, and better nutrition also improved public health.

During the Industrial Revolution, Earth's population doubled to one billion. It doubled again over the next hundred years. The advancements in science, technology, and medicine had dramatically increased the life expectancy of the population. By the middle of the twentieth century, humans appeared to have access to unlimited resources. However, the first disadvantages of all the breakthroughs and discoveries were starting to become apparent. These included land erosion from deforestation for housing, the loss of large areas of habitat for agricultural purposes, the drainage of wetlands, the depletion of forests for logging, and the extinction or decline of many species that were overharvested (such as whales, bison, and passenger pigeons).

In Ontario alone, the Carolinian forests were essentially eliminated to make room for agriculture, the white pine forests were destroyed when the pine trees were harvested for shipbuilding in England, and the beavers were trapped until their populations were greatly reduced (and saved only by a change in fashion in Europe). Ontario was home to massive passenger pigeon populations, but the pigeons were hunted and their habitat was destroyed, driving them to extinction.

Human Demographics

In 2000 CE, the worldwide annual growth rate for the human population was 1.26 %. Population experts expect the rate of growth to decline, but, even so, the human population will probably exceed 9 billion by 2050. The population growth rates of individual nations vary widely, ranging from much less than 1 % to more than 3 % (**Figure 3(a)**). Canada's growth rate is about 1 %. Industrialized countries of Western Europe have achieved nearly zero population growth (ZPG), but other countries, particularly those in Africa, Latin America, and Asia, will experience huge increases in their populations over the next 20 to 25 years (**Figure 3(b)**).

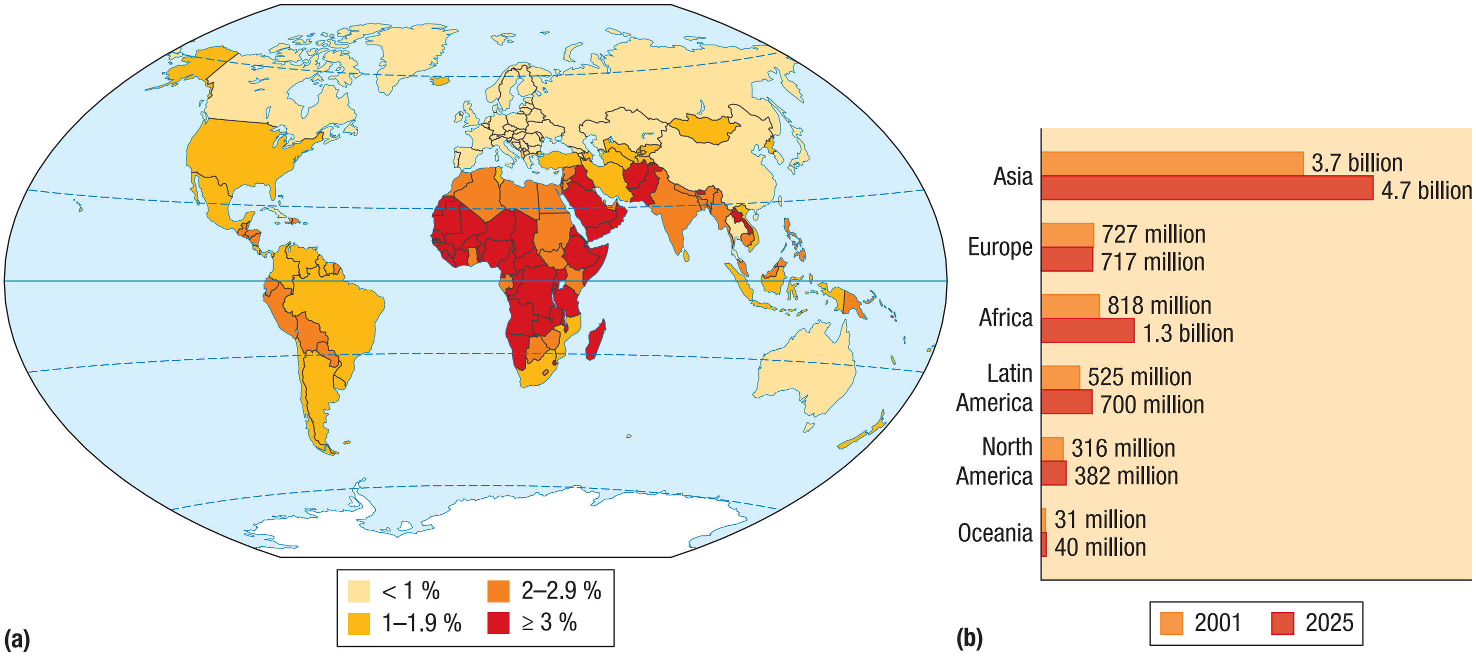
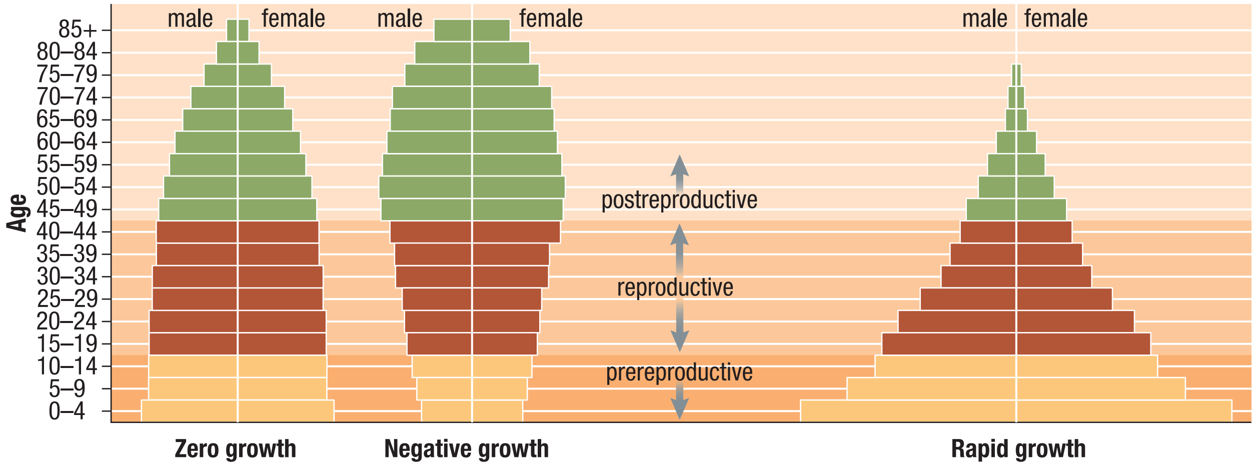


Figure 3 (a) In 2001, mean annual population growth rates varied among countries and continents. (b) In some regions, the population is projected to increase greatly by 2025 (red), compared with the population size in 2001 (orange). The population of Europe will likely decline.

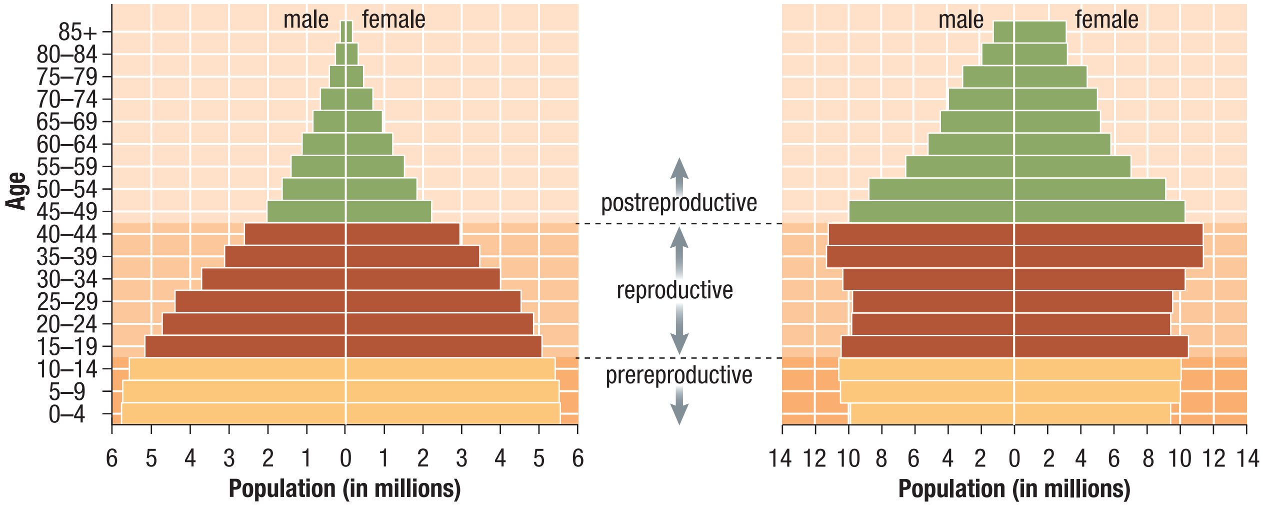
Age Structure

Demographers are often interested in the age structure of a population. This is the categorization of a population in a country or community by age groups. For all long-lived species, differences in age structure are a major determinant of differences in population growth rates. A **population pyramid** (also known as an age pyramid) is one way that demographers represent age distribution across a population. It is a horizontal bar graph that illustrates the distribution of different age groups in a population, with the number of males on the left and the number of females on the right (**Figure 4**). WEB LINK

population pyramid a tool that shows the distribution of ages among the males and females in a population



(a) hypothetical age distributions for populations with different growth rates



(b) age pyramid for Mexico in 2000

(c) age pyramid for the United States in 2000

Figure 4 (a) Age structure pyramids differ for countries with zero, negative, and rapid population growth rates. The width of each bar represents the proportion of the population in each age group. Age structures of (b) Mexico and (c) the United States in 2000 (measured in millions of people) suggest that these countries are experiencing different growth rates.

Age pyramids for a stationary population, with no overall population growth or loss (ZPG), have a small base and approximately the same numbers in each age group, although the numbers in the older age groups tend to taper off (Figure 4(a)). An age pyramid for a declining population has a narrow base with a higher proportion of the population in the older age groups. An age pyramid for a rapidly expanding population has a broad base, which indicates a high proportion of children in the population and a much lower proportion of people in the older age groups. Mexico's age pyramid

(Figure 4(b)) reflects expansive growth. An age pyramid for stable population growth has indentations that even out, reflecting slow growth over a period of time. However, the numbers for the older age groups again tend to taper off. The age pyramid for the United States (Figure 4(c)) reflects stable population growth.

Canada's Aboriginal Peoples

Aboriginal peoples descendants of First Nation, Métis, or Inuit people

In the 2006 Census of Canada, 1 172 790 respondents, or about 3.8 % of Canada's population, identified themselves as **Aboriginal peoples** (**Table 4**). People may identify themselves as Aboriginal if they are

- Registered or Treaty Indians or members of a band or First Nation
- Métis: people with both First Nations and European ancestry
- Inuit: Aboriginal people located north of the tree line in Canada or in the Northwest Territories, Nunavut, or northern Québec and Labrador

Note in Table 4 that the total number of Aboriginal peoples is higher than the number who identify with each of the three groups.

Table 4 Some Demographics of Aboriginal Peoples in Canada

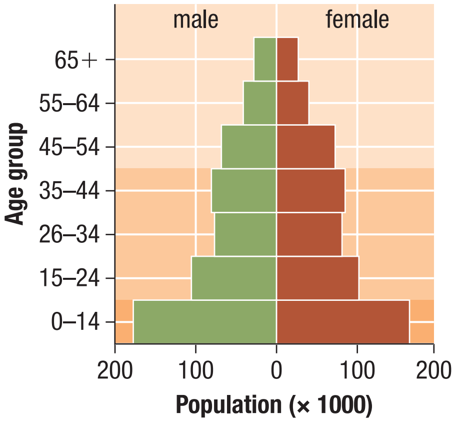
	Total Aboriginal	First Nations	Métis	Inuit	Total non-Aboriginal
Total population	1 172 785	698 025	389 780	50 480	30 068 240
Percentage of total Canadian population	3.8	1.3	1.2	0.2	96.2
Predominant locations	n/a	Winnipeg, Vancouver, Edmonton, Toronto, Saskatoon, Northwest Territories, and Yukon	Alberta, Manitoba, and Ontario	Nunavut, northern Québec, Newfoundland and Labrador, and Northwest Territories	widespread; largest populations in Toronto, Montreal, and parts of Vancouver
Median age	n/a	24.9	29.5	21.5	39.7

In 2006, the largest Aboriginal populations in Canada were in Ontario and the four western provinces, ranging from 242 495 in Ontario to 141 890 in Saskatchewan. The provinces and territories with the highest proportion of Aboriginal populations were Nunavut (85.0 %), the Northwest Territories (50.3 %), Yukon (25.1 %), Manitoba (15.5 %), and Saskatchewan (14.9 %). According to the 2006 census data, Aboriginal peoples in Canada are increasingly living in urban areas, with only 46 % living in rural areas.

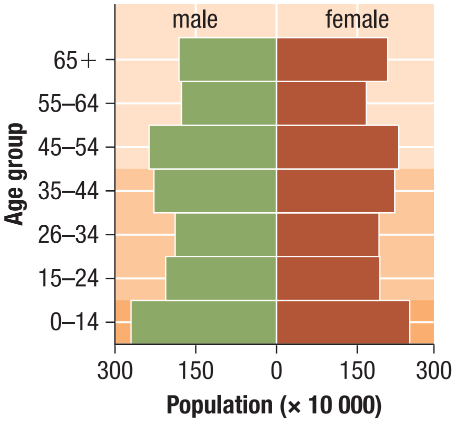
Aboriginal peoples are very diverse. They speak many different languages, enjoy different cultural practices, and participate in varying forms of government. They have always had a strong relationship with the land and its resources. Instead of the market-based approach to property, Aboriginal people do not view the land as being "owned" by any person. They believe that they are the custodians of the land for future generations. These differences were poorly understood by the European settlers who came to Canada in the late eighteenth century. The settlers initially encouraged and eventually forced Aboriginal peoples to assimilate into the European culture. Treaties were drawn up by the Government of Canada for the purpose of resettlement, attempting to extinguish the rights of Aboriginal peoples to their land. Consequently, Aboriginal land use and resource development have been affected.

Recent court decisions have upheld the rights of Aboriginal peoples to their land and its resources, returning their entitlement to the use of the natural resources over and above any other groups. The only exceptions are situations in which conservation of a natural resource takes priority. Any other interference in the name of public interest is unacceptable, according to the Supreme Court of Canada. These legal decisions are providing more opportunities for Aboriginal communities to participate in joint government ventures and resource partnerships in forestry, fisheries, and wildlife boards across Canada.

The demographics of the Aboriginal population in Canada differ greatly from the demographics of the non-Aboriginal population. The age pyramids in **Figure 5** show that the Aboriginal population has a much different population growth pattern than the non-Aboriginal population. The Aboriginal pyramid reflects an expanding population. The broad base indicates a high population of children, a rapid rate of population growth, and a low population of older people. The non-Aboriginal population pyramid reflects a much slower growth pattern.



(a) Aboriginal identity population



(b) non-Aboriginal identity population

Figure 5 Population pyramids for (a) the Aboriginal population and (b) the non-Aboriginal population in Canada based on the 2006 Census. The scale along the horizontal line of each pyramid is different because the overall population size is different for Aboriginal and non-Aboriginal people in Canada.

Until very recently, many environmental and resource management decisions have been made without Aboriginal consultation or involvement and, as a result, have often had negative effects on the health and well-being of Aboriginal communities. The difference in the age pyramids in Figure 5 indicates that the Aboriginal population will be increasing over the next few decades, possibly leading to increased Aboriginal involvement in these types of decisions.

Population Growth and Economic Development

The relationship between population growth and economic development has been studied extensively. The conventional view is that population growth means more people competing for limited natural and economic resources. The consequences include more individuals to be cared for, lower per capita income, and generally a lower standard of living compared with countries that have a lower birth rate.

demographic transition model a diagram that illustrates changes in how people live to explain shifts in population sizes

The relationship between a country's population growth and its economic development may follow the trends depicted by the **demographic transition model** (**Figure 6**). This model describes historical changes in demographic patterns in the industrialized countries of Western Europe. However, we do not know if it accurately predicts the future for developing nations.

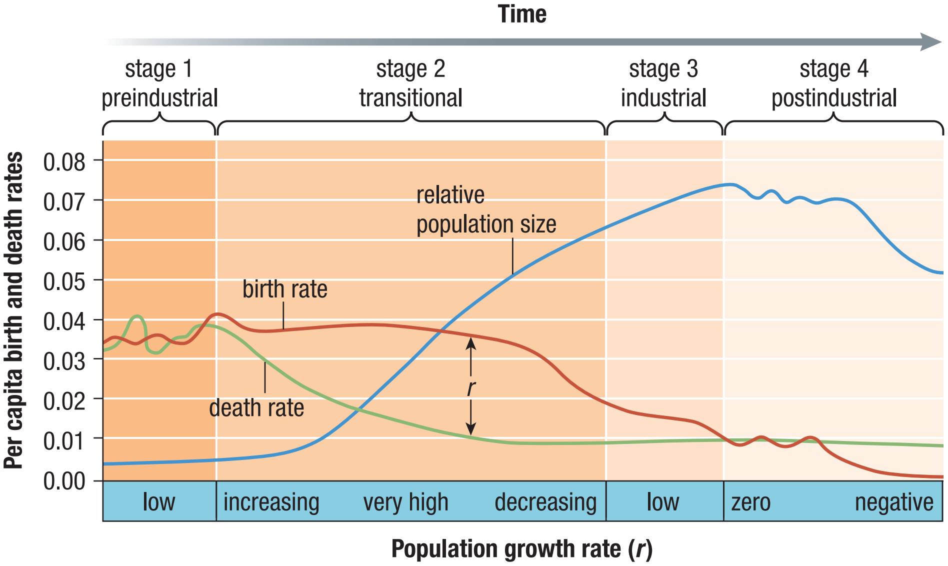


Figure 6 The demographic transition model describes changes in the birth and death rates and relative population size as a country passes through four stages of economic development. The bottom bar describes the net population growth rate, *r*.

According to this model, during a country's pre-industrial stage, birth and death rates are high, and the population grows slowly. Industrialization begins a transitional stage, when food production rises and health care and sanitation improve. As you learned earlier, improvements in public health reduce the death rate, causing the population to grow rapidly. Then, however, the cost of supporting larger families discourages parents from having as many children. The birth rate declines, causing a drop in the rate of population growth. By the time that a population has reached the industrial stage, population growth slows dramatically. More people move to cities, and urban couples often choose to accumulate material goods instead of having large families. As you can see, ZPG is reached in the post-industrial stage. Eventually, the birth rate falls below the death rate, *r* falls below zero, and the population size begins to decrease.

Today, the United States, Canada, Australia, Japan, Russia, and most of Western Europe are in the industrial stage. Their growth rates are slowly decreasing. In Germany, Bulgaria, Hungary, and other European countries, birth rates are lower than death rates. Populations are shrinking, indicating entry into the post-industrial stage. Kenya and other less industrialized countries are in the transitional stage, but they may not have enough skilled workers or enough capital to make the transition to the industrial stage. As a result, many poorer nations may stay in the transitional stage. Developing countries experience rapid population increase because they experience a decline in death rate associated with the transitional stage without a decrease in birth rate associated with the industrial and post-industrial stages.

Planned Reproduction

Most governments realize that increased population size is now a major factor that causes resource depletion, excessive pollution, and an overall decline in quality of life. The principles of population ecology demonstrate that, to shrink population size, the rate of population growth must be slowed by decreasing the birth rate or increasing the death rate. Increasing mortality is neither a rational nor humane means of population control. Some governments encourage reproductive alternatives in an attempt to lower the birth rate. In several countries, however, this is unlawful.

To achieve ZPG, the average **replacement rate** (the rate at which parents have children to "replace" them) should be just slightly higher than two children per couple. This is necessary because some female children die before reaching reproductive age or do not have children. Today's replacement rate averages about 2.5 children in less industrialized countries and 2.1 children in more industrialized countries (**Figure 7**). However, even if each couple on Earth produced only two children, the human population would continue to grow for at least another 60 years. Continued population growth is inevitable because today's children, who outnumber adults, will soon mature and reproduce. The worldwide population will stabilize only when the age distributions for all countries resemble the age distributions for countries with ZPG.

replacement rate the rate at which people have children to "replace" them when they die

Figure 7 (a) Families living in more industrialized countries often have smaller families. These countries have an average replacement rate of 2.1 children, approaching ZPG. (b) Families living in less industrialized countries tend to have larger families. These countries have an average replacement rate of 2.5 children, so their populations will continue to grow.

Reproductive alternatives can be as simple as a woman waiting to have her first child. This delay will reduce the average family size and slow population growth by increasing generation time. Imagine two populations in which each woman produces two offspring. In the first population, women begin reproducing at 32 years of age. In the second, women begin reproducing at 16 years of age. After 32 years, women in the first population will be giving birth to their first offspring, but women in the second population will be new grandmothers (assuming that their daughters also bear their first children at 16 years of age). After 64 years, women in the first population will be new grandmothers, but women in the second population will witness the birth of their first great-great grandchildren. Obviously, the first population will grow much more slowly than the second.

13.1 Review

Summary

- Human population growth changes over time and varies significantly by region.
- Agricultural and industrial revolutions have led to surges in the human population.
- Advancements in science, technology, and medicine have led to decreases in the mortality rate.
- Age pyramids represent age distributions across a population.
- Demographics for the Aboriginal population in Canada suggest that there may be a population increase in the next decade, due to a large number of young people.
- The relationship between population growth and economic development in many countries can be represented by the demographic transition model.

Questions

1. Can a population increase even though its growth rate is decreasing? Explain your answer. K/U
2. Explain why immigration and emigration are not included in world population formulas. K/U T/I
3. Explain how birth and death rates determine the rate of natural population growth. K/U
4. The world's population is still growing, but at a slower rate. Use the Internet or other sources to help you answer the following questions. K/U T/I
   (a) Do you think that Earth has a finite carrying capacity? What will happen to the world population if a finite carrying capacity is reached?
   (b) If this growth trend continues, we will eventually reach ZPG. Do you think the planet can support the world population until that time? Why or why not?
5. Sketch two models of population growth, based on the information in the final paragraph on page 651. Show how each population grows if a woman in each generation has her first child at 16 or 32. Create a list of assumptions (for example, all females live the entire time, and each woman only has two children). Present the data visually in a table, a graph, or another format. K/U T/I C
6. Choose a country and research its population trends over the last 50 years. K/U T/I
   (a) By what percentage has the population increased or decreased?
   (b) What types of government or economic policies are being put in place to respond to the population dynamics?
   (c) Why do some countries have population growth policies, while others do not?
7. Use the population pyramid for a hypothetical country in **Figure 8** to answer the following questions. K/U T/I A

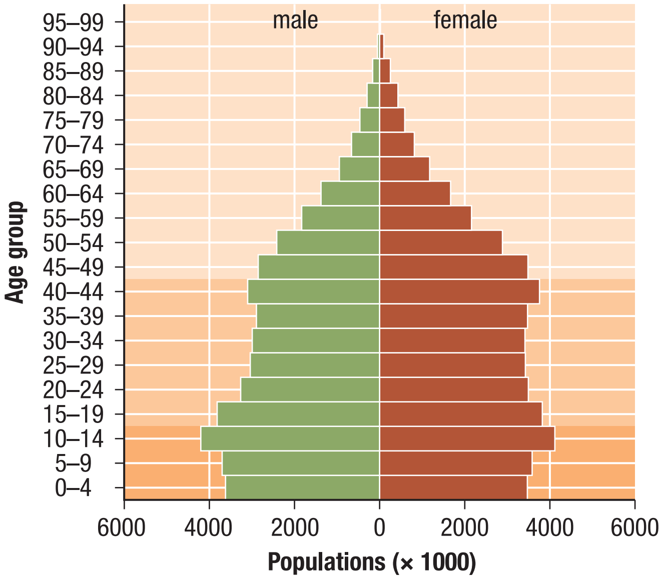


Figure 8 Population pyramid

   (a) What does the shape of the pyramid tell you about the population of this country?
   (b) What types of growth patterns might be expected in the future?
   (c) What types of issues might the government of this country be facing, based on the population data?
   (d) Based on the shape of the pyramid, would you classify this country as a developed or developing country? Which demographic model stage is it likely in? Explain your reasoning.

WEB LINK

Implications of Human Population Growth

The global rate of human population growth peaked in the mid 1900s, but the number of people living on the planet and sharing its finite resources, such as water and food, has more than doubled since 1950. This exponential expansion of the human population comes with environmental concerns. Human population growth and the resulting demand for resources has either caused or intensified many environmental issues, including deforestation, the depletion of fish reserves, species loss, the over-zealous extraction and use of fossil fuel resources, and climate change.

A sustainable population is a population that can survive over thousands of years without running out of resources or damaging its environmental niche. To accomplish this, we must not generate more wastes than natural processes can return to the biosphere. The wastes that are generated must not be harmful to the planet.

Earth's carrying capacity is the population that Earth can sustain, given the available quantity of life-supporting resources. Carrying capacity can be increased by the discovery and use of new resources, such as clean energy supplies and fertile land. It can be decreased by resource exhaustion, such as desertification and deforestation. It can also be decreased by pollution caused by waste buildup, such as water pollution. More than any other species on Earth, humans have the ability to alter their environment directly. In this chapter, you will examine some of the global impacts and implications of human population growth.

Urbanization

The human population reached a milestone in 2007. According to the United Nations, 2007 marked the first time that more people lived in urban areas than in rural areas (**Figure 1**). In fact, more than 80 % of Canadians now live in urban areas. Definitions of an urban area vary from country to country but, according to Statistics Canada, an urban area has a cluster of at least 1000 people and a minimum population density of at least 400 people per square kilometre.

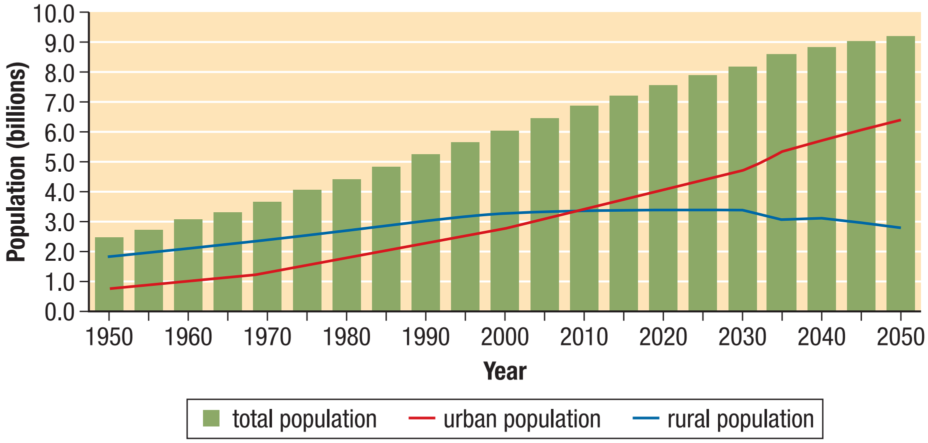


Figure 1 The projected population of urban areas and rural areas, as well as the total world population, through the year 2050

Migration into urban areas occurs for several reasons. Farming depends on unpredictable environmental conditions and can be problematic when environmental conditions are less than ideal. In addition, the industrialization of agriculture has reduced the number of small- and medium-sized farms. This has reduced the rural labour market, so people move into cities to search for other economic opportunities.

Urbanization also occurs when people and businesses take advantage of the proximity and diversity of city living. Industrial cities that developed in the mid-nineteenth to early twentieth centuries for the manufacturing of goods tended to be compact, with businesses located in their core. Most people walked to work or took public transportation (streetcars), since the growth of these cities usually followed the transportation routes. Theoretically, the concentration of populations in cities could reduce the time and expense of transportation and improve the opportunities for jobs, education, and housing. However, the widespread use of cars in the late 1940s led to suburban sprawl and development that altered the form and function of cities.

As cities push outward to accommodate their ever-growing populations, tremendous pressure is put on the land that is used to produce food. The City of Toronto, for example, estimates that 330 km^2 of rural land was taken over for urban use between 1966 and 1986. Similar situations have also occurred in Montréal and Vancouver as their urban populations have expanded. These changes in land use affect the water cycle and disturb or destroy habitats. Impermeable surfaces, such as asphalt and concrete, reduce the ability of the ground to absorb water. Natural waterways are dammed and re-routed. Bogs and wetlands are drained and converted into building sites, adding to the amount of impermeable surface and destroying habitats. Emissions from vehicular traffic enter and pollute natural waterways, affecting both the water quality and the air quality.

Access to clean, safe water is an ongoing concern for cities today. Safe drinking water is still not available to all Canadians. Some Aboriginal peoples have less access to secure and safe water supplies even in urban areas, and some rural areas lack consistently clean, drinkable water. Water consumption for both domestic and commercial use continues to increase. Water is a renewable resource, yet the supply of clean, fresh water is steadily decreasing as demand exceeds supply in many parts of the world. Renewable resources can be fully replaced naturally over a period of time.

The quality of an urban environment is directly related to the health of its inhabitants and their quality of life. Population growth and economic development put pressure on the natural environment and create many local issues that need to be considered. For example, increased demands for transportation and energy create pollution and air quality issues. Sending solid waste to landfills creates pollution and is an inefficient use of land. Cities and their populations are large consumers of goods and services, draining the resources that they depend on for survival. For cities to be more sustainable, these key environmental issues cannot be ignored.

Research This

Creating a Sustainable City

Skills: Researching, Evaluating, Communicating, Defining the Issue, Identifying Alternatives

SKILLS HANDBOOK A4.1

Cities continue to be perceived as having an economic advantage over rural areas. However, urban populations consume vast amounts of natural resources and are major sources of pollution and greenhouse gas emissions. Satisfying the needs of today's city dwellers without compromising our ability to meet the needs of tomorrow is a primary challenge of sustainable city development. In this activity, you will research one issue that has an environmental impact on sustainable living.

1. Choose one of the following urban issues: air pollution, noise pollution, water pollution, light pollution, waste disposal, or heating and cooling energy demands.
2. Research the causes, the environmental implications, and the short-term and long-term environmental effects of the issue you chose.
3. Research any strategic visions and/or practical sustainable plans that already exist.

A. For the urban issue you chose, what are the causes of greatest concern? T/I

B. How do the short-term and long-term impacts of this issue affect the quality of the life and health of the city dwellers and the surrounding areas? T/I

C. What innovations or alternatives have been introduced to help lessen the environmental impact? T/I

D. Are there options for dealing with this issue that have not been implemented, but could be or should be? T/I

E. Create a visual or audiovisual presentation to give your classmates a brief overview of this issue and the proposed solutions. C

WEB LINK

Feeding the World

Humans need food to survive. Historically, people secured food through two methods: agriculture, and hunting and gathering. Since the Industrial Revolution, technological enhancements in farming practices and equipment have increased global food production. Enough food is produced to feed all the people in the world adequately, and yet tens of millions continue to suffer from malnutrition and starvation. **Malnutrition** is a condition that develops when the body does not get the right amounts of energy-rich foods, proteins, vitamins, minerals, and other nutrients needed to maintain healthy tissues and organ function. In 2010, according to the United Nations Food and Agricultural Organization, 925 million people in the world were undernourished. The United Nations defines the minimum critical diet, or the minimum amount of food that should be consumed each day, as no less than 9900 J (joules). Below this amount, chronic malnutrition may result. **Figure 2** shows the unequal access to food energy intake around the world. CAREER LINK

malnutrition a condition that develops when the body lacks proper nutrients

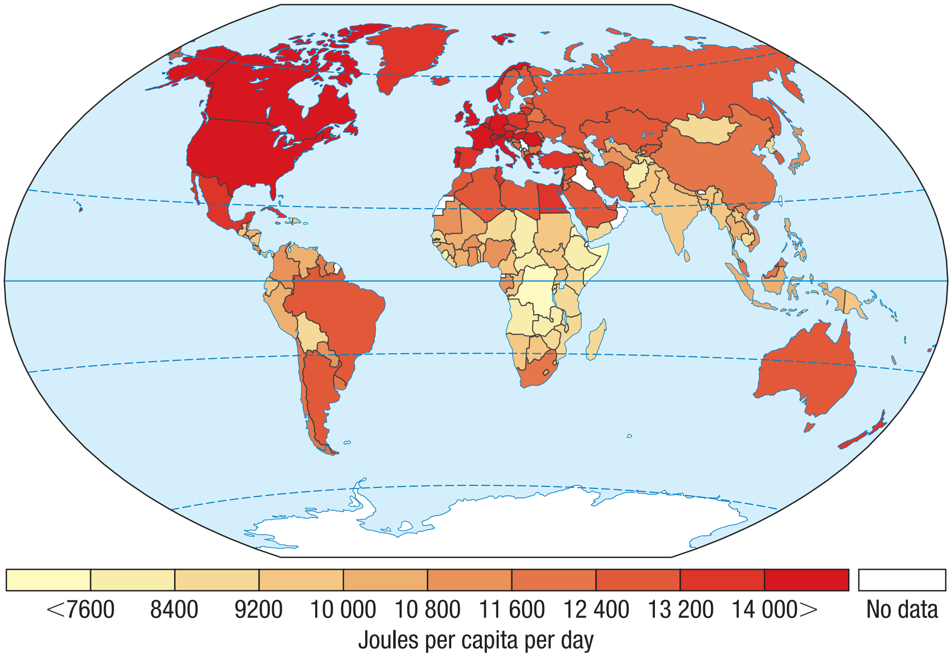


Figure 2 Global food intake is measured in food energy intake of joules per day. A daily intake of 9900 J per day is considered adequate.

The causes of world hunger are many and complex. According to the World Food Programme, there are five key causes of hunger:

- Natural disasters: Floods, tropical storms, long periods of drought, and other natural disasters have catastrophic consequences for food production in developing countries.
- Conflict: War disrupts agricultural production, and some governments spend more on arms than on social programs. Refugees are uprooted and moved from the land that was once used for food production.
- Poverty: People who live in poverty do not have the necessary resources, land, tools, or money to grow or buy food.
- Poor agricultural infrastructure: Many areas of the world lack adequate roads, storage facilities, and irrigation. The results are high transportation costs, lack of warehouses, and unreliable water supplies.
- Over-exploitation of the environment: Poor farming practices, deforestation, overcropping, and overgrazing are exhausting the fertility of the soil. In addition, over-consumption by wealthier nations and rapid population growth in developing nations strain natural resources and make it harder for many people to feed themselves.

Food Sources

Historically, humans have depended on three general sources for their food supply: croplands, rangelands, and ocean fisheries. Croplands mostly produce grains and provide about 77 % of the world's food. Rangelands produce meat, mostly from grazing livestock, and provide about 16 % of the world's food. Ocean fisheries provide about 7 % of the world's food.

Since 1950, there has been a staggering increase in global food production from all three sources. Technological advances, such as the increased use of tractors and farm machinery, as well as high-tech fishing boats and gear, are the primary reason for this increase. Other reasons include synthetic fertilizers, irrigation, pesticides, and high-yield varieties of wheat, rice, and corn. In addition, food production has increased due to the use of densely populated feedlots and enclosed pens for raising cattle, pigs, and chickens, as well as aquaculture ponds and ocean cages for raising some types of fish and shellfish.

We face important challenges as we attempt to increase food production without causing serious environmental harm. To feed the world's 7 billion people, we must produce and equitably distribute more food than has been produced since agriculture began about 10 000 years ago. Some analysts believe that we can accomplish this, mostly through genetic engineering. Other analysts have doubts. They are concerned that environmental degradation, pollution, lack of water for irrigation, overgrazing by livestock, overfishing, and the loss of vital ecological services may limit future food production. A key problem is human activities, which continue to degrade more of Earth's net primary productivity.

Since the beginning of agriculture, about 10 000 species have been used as sources of food for people and livestock. Today, only 14 plant and 8 terrestrial animal species supply an estimated 90 % of our global intake of calories. Just three grain crops—wheat, rice, and corn—provide more than half of the calories that people consume. Two-thirds of the people in the world survive primarily on these traditional grains, mostly because they cannot afford more meat and other products of domesticated livestock, which also consume grain. Such a dependence on just a few plant species for food shows a dramatic reduction in agricultural biodiversity.

industrialized agriculture the growth of food using machines and synthetic fertilizers and pesticides

Fish and shellfish are important sources of food for about 1 billion people, mostly in Asia and in coastal areas of developing countries. On a global scale, however, fish and shellfish supply only 7 % of the world's food and about 6 % of the protein in the human diet.

There are two major agricultural systems: industrialized agriculture and traditional agriculture. **Industrialized agriculture** uses large amounts of fossil fuel energy, water, and synthetic pesticides to produce single crops (monocultures) or livestock animals to sell (**Figure 3**). Industrialized agriculture accounts for 80 % of the world's food supply. It is the system that is used on about one-fourth of all croplands, mostly in developed countries, but it has spread to some developing countries since the mid-1960s. Plantation agriculture is a form of industrialized agriculture that is used primarily in tropical developing countries. It involves growing cash crops, such as bananas, coffee, soybeans, sugar cane, cocoa, and vegetables.

Figure 3 Industrialized agriculture produces large amounts of food, but at an environmental cost.

An increasing amount of livestock production in developed countries is industrialized. Large numbers of cattle are brought to densely populated feedlots, where they are fattened for about four months before they are slaughtered. Most pigs and chickens in developed countries spend their lives in densely populated pens and cages, and eat mostly grain grown in croplands.

traditional agriculture the growth of food by hand, using natural fertilizers and pesticides

Traditional agriculture uses mostly human and animal labour to produce crops. It can be subsistence, producing only enough to feed the farmer's own family, or it can be intensive, producing enough to feed the family and sell for income. Traditional agriculture is the system that is used by about 2.7 billion people (39 % of the population) in developing countries and provides about 20 % of the world's food supply.

In traditional subsistence agriculture, farmers use mostly human and animal labour to produce only enough crops or livestock for their own family to survive. Examples of this very low input type of agriculture include numerous forms of shifting cultivation in tropical forests, as well as nomadic livestock herding. In traditional intensive agriculture, farmers increase their inputs of human and animal labour, fertilizer, and water to get a higher yield per area of cultivated land. They produce enough food to feed their family, plus a surplus to sell for income.

Croplands, like natural ecosystems, provide important ecological and economic services. Indeed, agriculture is the world's largest industry, providing a living for roughly 1.3 billion people (**Figure 4**).

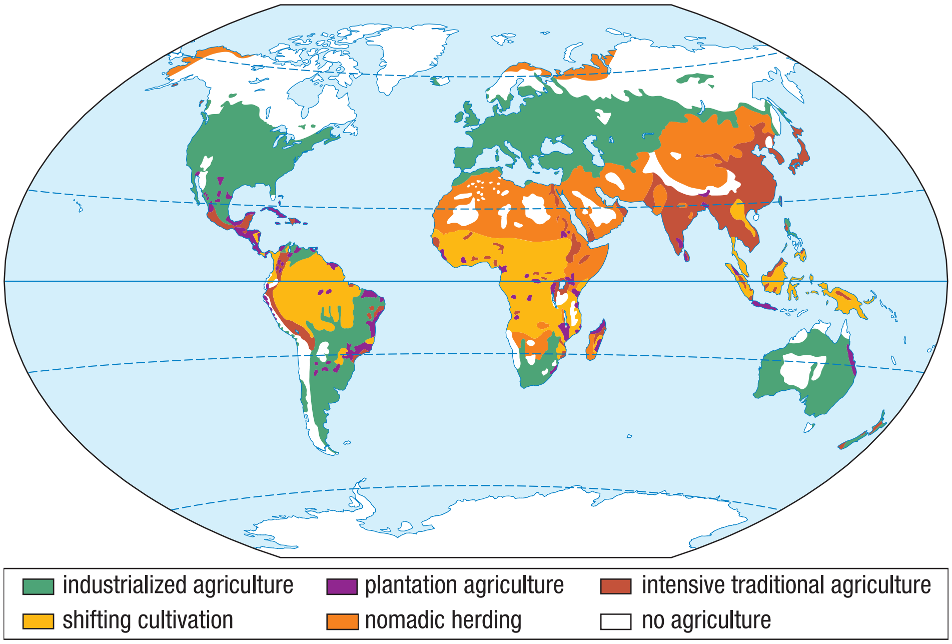


Figure 4 The locations of the major agricultural systems. Excluding Antarctica and Greenland, agricultural systems cover almost one-third of Earth's land surface.

Agriculture in Canada

Canada has 5 % of the world's available land. In 2011, the agriculture industry contributed $87.9 billion to Canada's economy. Canada is the world's fourth-largest exporter of food. Clearly, Canada is a key player in supplying the world with food.

The number of farms in Canada has been declining in recent decades, but the average size of farms has been increasing due to mechanization, economic pressures, and social changes, among other factors. The net result is that the amount of land farmed in Canada—68 million hectares—has remained about the same over the past 50 years. Canada produces an agricultural surplus and exports $21 billion worth of raw and value-added goods, including grains, oilseeds, fruits, vegetables, and meats, to 200 different countries.

Much of Canada is too cool, dry, rocky, and/or lacking adequate soil for growing (**Figure 5**). Only about 7 % of our terrestrial area is considered to be agricultural land. Precipitation, soil quality, and temperature are among the factors that determine where agriculture is practised in Canada. The Prairie provinces account for 83 % of the farmland, while Ontario and Québec have a combined total of 13 %. Dry conditions, seasonal temperatures, and optimum soil make the Prairies an ideal environment for producing most of Canada's wheat, barley, oats, soybeans, canola, hay, and cattle. Ontario and Québec produce most of the country's poultry, pigs, dairy products, and maple syrup. British Columbia is famous for its fruit, wine, and salmon. The Maritimes are best known for their potatoes and seafood.

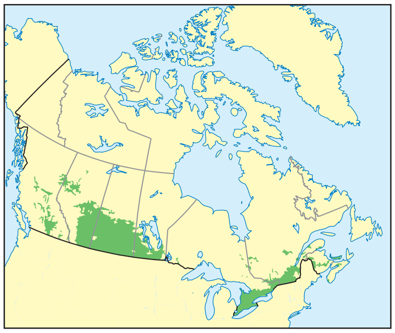


Figure 5 The distribution of agricultural land in Canada

Energy Use in the Human Food Web

energy pyramid a tool that is used by researchers to track the usable energy in a food web

trophic level one level of a food web

Ecologists use **energy pyramids**: models that depict the energy flow from consumers through a food chain or web (**Figure 6**). Each energy transfer level in a food chain or web is referred to as a **trophic level**. The pyramidal shape of an energy pyramid shows that the energy flow through an ecosystem is inefficient. In fact, only about 10 % of the energy from one level moves to the next. Figure 6 shows that more energy can be obtained by humans through the consumption of producers (grains, fruits, and vegetables) than through the consumption of higher-level consumers (such as cattle and other livestock).

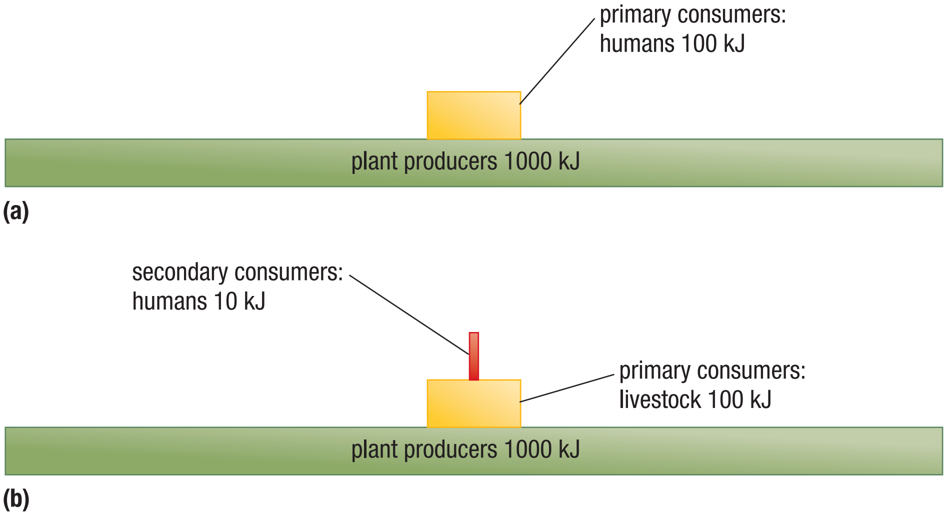


Figure 6 These energy pyramids show the transfer of energy between (a) two levels and (b) three levels. Notice that, if humans are the primary consumers, they get more energy from the plant producers.

The energy in agriculture can also be measured in terms of the energy that goes into producing a unit of food. Industrialized farming is considered high-input farming because there are many resources that go into producing food. For example, in the United States, industrialized agriculture consumes about 17 % of all the commercial energy in the country each year. Canadian values would be similar. Considering the energy that is used to grow, store, process, package, transport, refrigerate, and cook all the plant and animal food, about 10 units of non-renewable fossil fuel energy are needed to put 1 unit of food energy on the table. Additional energy is needed for consumers to shop and purchase food, and prepare it before consuming it. By comparison, every unit of energy from human labour in traditional subsistence farming provides at least 1 unit of food energy. Traditional intensive farming provides up to 10 units of food energy.

Another way to measure the energy in agriculture is to calculate agriculture's ecological footprint. The land that is used to raise crops or livestock, the fertilizer and pesticides that can contaminate surrounding lands, the space that is needed for waste disposal, the water that is needed for irrigation and sustaining livestock, and the fossil fuels that are burned during food production contribute to the size of agriculture's ecological footprint. All of these factors contribute to climate change. Burning fossil fuels sends greenhouse gases into the atmosphere, and clearing land to plant crops and raise livestock eliminates trees, which are needed to remove CO_2 from the air. Livestock that are ruminants (cattle, sheep, and goats) contribute to greenhouse gas emissions by releasing methane gas. Therefore, the food choices we make as consumers can make an environmental difference. For example, choosing locally grown grains and other food sources that are low on the food pyramid conserves more energy and helps to lessen agriculture's ecological footprint.

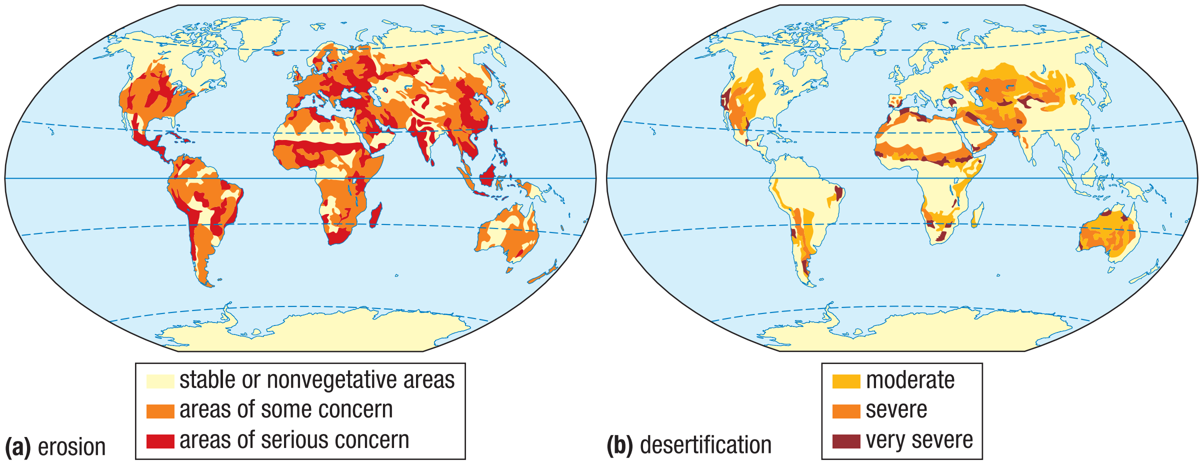
Threats to Soil

The next time you are shopping for groceries or having lunch in a fast-food restaurant, take a moment to remember that most food, even highly processed food, comes from the ground. This is why preserving the world's topsoil is the key to producing enough food to feed the world's growing population. Land degradation occurs when natural or human-induced processes decrease the future ability of the land to support crops, livestock, or wild species. The key threats to the land include soil erosion and lost fertility, desertification, and **salinization**—increased amounts of salt in the soil.

salinization the addition of salt products due to the overuse of resources

Soil erosion is the movement of soil components from one place to another. Some soil erosion is natural, caused by wind and flowing water. In undisturbed vegetated ecosystems, the roots of plants help to anchor the soil, and soil is not usually lost faster than it forms. Soil becomes more vulnerable to erosion when human activities destroy plant cover. Some of the activities that destroy plant cover are farming, logging, construction, overgrazing by livestock, off-road vehicle use, and deliberate burning of vegetation. About 60 % of eroded soil ends up as sediment in nearby surface water, where it can pollute the water; kill fish and shellfish; and clog irrigation ditches, boat channels, reservoirs, and lakes. Overall, soil erosion causes an estimated $400 billion worth of damage worldwide each year (**Figure 7(a)**). Some methods to stop erosion are using rows of trees as windbreaks, building terraces on steep slopes, and using conservation tillage systems and crop rotation.

Desertification occurs when the productive potential of arid or semi-arid land falls by 10 % or more because of a combination of natural climate changes that cause prolonged drought and human activities that reduce or degrade topsoil. Desertification can be moderate (a 10 to 25 % drop), severe (a 25 to 50 % drop) or very severe (50 % or more, usually creating huge gullies and sand dunes). In extreme cases, desertification leads to what we call desert. About 30 % of the world's land and 70 % of all drylands suffer from the effects of desertification (**Figure 7(b)**). We cannot control when or where prolonged droughts occur, but we can reduce overgrazing, deforestation, and destructive forms of planting, irrigation, and mining that leave the soil barren.



(a) erosion

(b) desertification

Figure 7 Areas of significant (a) soil erosion and (b) desertification in the world

One method for keeping the soil moist is irrigation, which involves channelling water to moisten land that does not receive enough rainfall to support agriculture. Irrigation is one way that we have expanded our growing capacity around the world. About 20 % of the world's cropland is irrigated, and this 20 % produces almost 40 % of the world's food. In Canada, the Prairies and the interior of British Columbia rely heavily on irrigation. Alberta uses about 60 % of all irrigation resources in Canada.

However, irrigation has a drawback. Most irrigation water is a dilute solution of various salts that are picked up as the water flows through soil and rocks. The water that is not absorbed into the soil evaporates, leaving behind a thin crust of dissolved salts, such as sodium chloride, in the topsoil. Over time, the salts accumulate in the upper soil layers, causing salinization, which stunts crop growth, lowers crop yields, and eventually kills plants and ruins the land.

Soil erosion, desertification, and salinization, combined with overgrazing and overplanting, contribute to a loss of soil fertility. When the nutrients are stripped from the soil, it can no longer support agriculture. Some crops, such as corn, strip the soil of nutrients, so farmers may alternate these crops with other crops from season to season. Fertilizers, ranging from natural manure and plant compost to commercial inorganic chemicals such as nitrogen and phosphorus, can also replace lost nutrients.

Sustainable Agriculture

sustainable agriculture (low-input agriculture) the growth of food using less energy and fewer resources than industrialized agriculture uses

organic agriculture a method of growing food without using synthetic fertilizers and pesticides

One way to reduce the harmful environmental effects of agriculture is to use sustainable or low-input technologies. **Sustainable agriculture** (or **low-input agriculture**) uses technologies that are based on ecological knowledge to increase yields, control pests, and build soil fertility, while using less energy. Sustainable agriculture helps to increase biodiversity because it involves planting a variety of crops each year. It may also use organic farming methods, which reduce the use of pesticides and synthetic fertilizers. **Organic agriculture** is a sustainable system of food production that is aimed at producing high-quality, nutritious food with little or no reliance on synthetic pesticides or synthetic fertilizers. Organic farmers, for example, use manure and tilled-in crop residues to help maintain and build soil fertility by increasing its carbon content. This can help to reduce runoff and improve water quality.

Livestock that are raised organically have improved living conditions and do not consume antibiotics or additives. Organic produce and livestock are free of antibiotics and growth hormones, genetically modified organisms, and irradiation. Globally, the organic agriculture industry is worth $35 billion per year and is growing rapidly throughout the world (**Figure 8**). In Canada, the sale of organic food is a $2.1 to $2.6 billion business, but about 80 % of this food is imported. For many people, choosing organic food is an integral part of a healthy lifestyle, which helps reduce their ecological footprint.

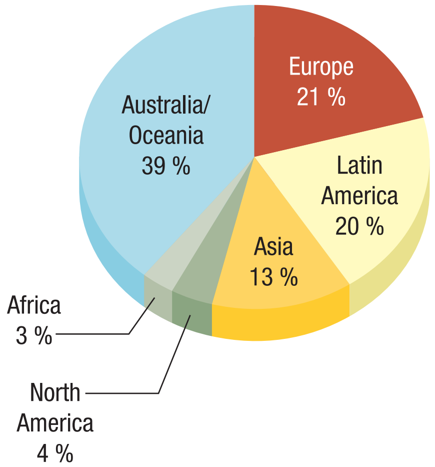


Figure 8 The share of the global area under organic management, per continent

To obtain organic certification, farmers in Canada have to follow strict regulations set out by the National Standard of Canada for Organic Agriculture. Currently, organic farming makes up only about 1.5 % of the agriculture in Canada, but it is growing at a rate of 20 % per year.

Aquatic Food Sources: The World's Fisheries

Not all of our food is produced on land. Approximately 95 million tonnes of wild fish and shellfish are caught in the world's oceans, rivers, and lakes each year. Another 45 million tonnes are farmed. These numbers are growing each year. At the current rate, researchers fear that our fisheries will soon be depleted beyond recovery.

Fish are renewable resources as long as the annual harvest leaves enough breeding stock to renew the species for the next year. Overfishing leaves too little breeding stock to maintain the population. Prolonged overfishing leads to commercial extinction, when the population of a species declines to the point where it is no longer profitable to fish for it. Fishing fleets then move to a new species or a new region, hoping that the overfished species will recover.

Since the 1950s, mechanized fishing has been growing. By the 1990s, the worldwide expansion of fishing grounds had peaked, and the fisheries quickly became overexploited. **Table 1** identifies the principal marine fishing areas of the world. Today, commercial fishing employs about 40 million people, and about 2 million motorized fishing boats operate around the world. Some common commercial fishing methods involve the use of longlines, drift nets, purse-seine nets, and trawl nets (**Figure 9**). Different methods are used, depending on the species of fish targeted. These methods are so efficient, however, that they have eliminated some fish species. International conservation groups are working to minimize the amount of **bycatch**: the unintended fish and other species that get caught in fishing nets. For example, "dolphin-safe" tuna is caught without a bycatch of dolphins.

Table 1 Capture Fisheries Production: Principal Marine Fishing Areas in 2008

Area	Production (in millions of tonnes)
northwest Pacific	20.1
southeast Pacific	11.8
western central Pacific	11.1
northeast Atlantic	8.6
eastern Indian Ocean	6.6
western Indian Ocean	4.1
eastern central Atlantic	3.4
northeast Pacific	2.6
southwest Atlantic	2.4
northwest Atlantic	2.0

bycatch marine and aquatic species that are captured because of their proximity to targeted species

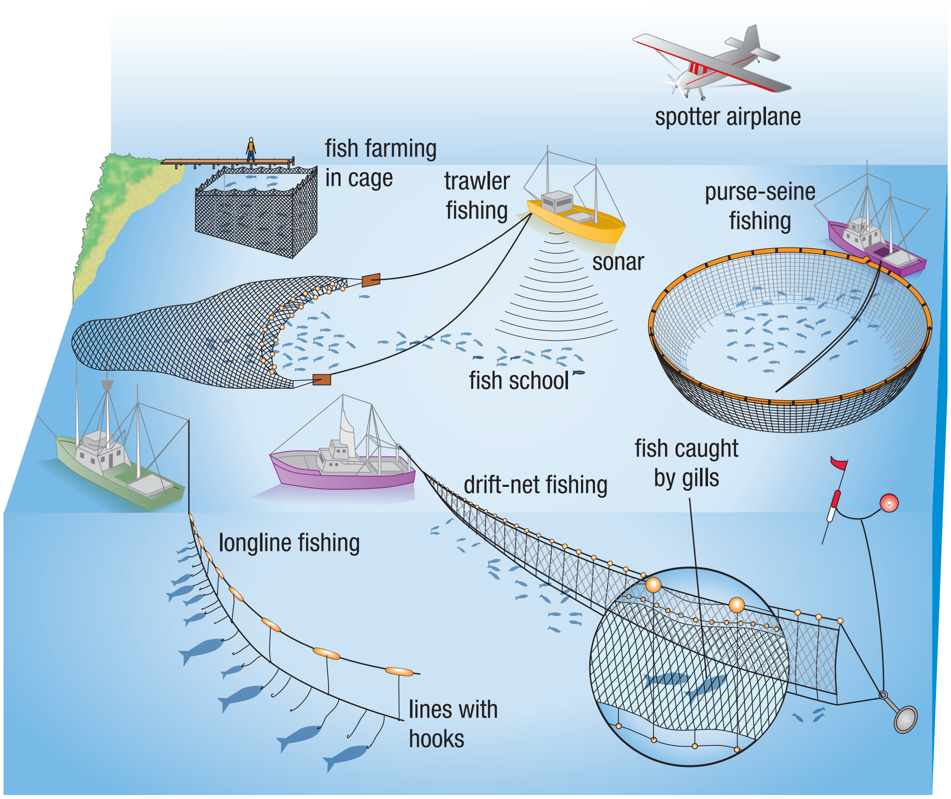


Figure 9 The major commercial fishing methods used to harvest marine species are very efficient. However, they have resulted in overharvesting the world's fisheries.

One way to combat the shrinking fish supply is to produce fish using **aquaculture**: the farming of aquatic organisms, such as fish, shellfish, and even plants. The term "aquaculture" refers to the cultivation of both marine and freshwater species and can range from land-based to open-ocean production. It is the world's fastest-growing type of food production and accounts for about one-third of the fish and shellfish we

aquaculture a method of raising fish and shellfish for crops eat. According to the United Nations Food and Agriculture Organization, by 2030, aquaculture will account for more than half of the fish that are produced for human consumption. China, the world leader, produces over two-thirds of the world's aquaculture output. Aquaculture is used in all the provinces of Canada and the Yukon. British Columbia and New Brunswick are the largest producers, accounting for 75 % of Canada's output. More than 70 species of fish, shellfish, and plants, including salmon, mussels, oysters, trout, and steelhead, are licensed for aquaculture in Canada.

Although aquaculture has the potential to make great contributions to the world's food supply, there are some drawbacks (**Table 2**). In some tropical countries, for example, natural habitats are destroyed when mangrove trees that normally root in salt water are removed to build pens for the fish. The roots of the trees have an important role in the tropical marine ecosystem. They provide a habitat for a variety of juvenile fish and invertebrates that hide from predators in the roots of the trees. The trees also prevent erosion during floods and storms by holding the soil in place.

Table 2 Pros and Cons of Aquaculture

Pros	Cons
It is highly efficient.	Large inputs of land, feed, and water are needed.
There are high yields in small volumes of water.	Large and concentrated outputs of waste are produced.
Increased yields are possible through cross-breeding and genetic engineering.	Mangrove forests are destroyed.
Overharvesting of conventional fisheries can be reduced.	Increased grain production is needed to feed some species.
Little fuel is used.	Fish can be killed by pesticide runoff from nearby cropland.
Profits are not tied to the price of oil.	Dense populations are vulnerable to disease.
Profits are high.	Tanks are too contaminated to use after about 5 years.

Research This

Low-Impact Diets

Skills: Researching, Analyzing, Evaluating, Communicating, Defining the Issue

SKILLS HANDBOOK A4.1

Do you know where most of your food comes from or how it is produced? You may be surprised. The food choices you make can have an indirect impact on the environment. In this activity, you will investigate the importance of the food choices you make.

1. Research three low-impact diets: a vegan/vegetarian diet, the 100 mile diet, and an organic and natural diet (no processed foods).
2. Determine the environmental impact of each diet and the environmental impact of your typical diet.

A. Where is each diet on the food chain? T/I

B. What are the environmental costs and benefits associated with each diet, in terms of energy and resources? T/I

C. Compare a vegan diet with a traditional meat diet in terms of the amount of land needed to feed an equal number of people. Which diet requires more land, and why? T/I

D. How might the area of the country where you live affect your choice of the diet that is best for the environment? T/I A

E. What foods are produced locally where you live? Are they available year-round or only seasonally? 🌐 T/I

F. Are there other factors to consider when making dietary choices, other than environmentalism? T/I A

🌐 WEB LINK

Water and Air

There are 34 million people living in Canada, and each person needs clean air and water. Urban areas are growing, putting a strain on existing water sources and the infrastructure that is needed to channel water to household faucets. Many people depend on water sources such as aquifers (groundwater storage reservoirs in the water cycle). While groundwater is a renewable source, reserves replenish relatively slowly so they have the potential to be depleted. In addition, urban development in watershed regions pollutes groundwater. Runoff from agriculture can also pollute groundwater and other water supplies, requiring additional monitoring and treatment to make drinking water safe.

Increased development and industry threaten our fresh air, as well. The quality of our air has a direct impact on our health and the natural environment, so we need our air to be as clean as possible. Air pollution can be caused by emissions of harmful gases (such as sulfur dioxide and nitrogen oxides) or particulates (such as soot) into the atmosphere. Air pollution can also be caused by disturbances to the normal composition of the air. For example, increased emissions of greenhouse gases, such as carbon dioxide, disrupt the balance of the natural carbon-oxygen cycle. When natural cycles are disrupted by the overproduction of industrial and vehicular emissions, the result is air pollution.

Water Supplies and Demand

Despite its importance, water is one of our most poorly managed resources. We waste it and pollute it. Many Canadians believe that we will have a freshwater shortage if we do not pay attention to its conservation. However, despite this apparent appreciation of the value of fresh water, we continue to waste it. Many of us use five times as much water per day as we believe we use.

Only a fraction of Earth's total volume of water is available to us as soil moisture, usable groundwater, water vapour, and surface water. Some 97.4 % of the world's total volume of water is found in oceans and saline lakes, and is therefore too salty for drinking, irrigation, and industry (except as a coolant). Most of the remaining 2.6 % that is fresh water is locked up in ice caps and glaciers or in groundwater that is too deep or salty to be used.

The world's freshwater supply is continuously collected, purified, recycled, and redistributed in the solar-powered hydrologic cycle. Water evaporates from bodies of water, land, and organisms into the atmosphere, where it condenses and falls back to Earth as precipitation. It flows across Earth's surface as runoff, entering wetlands, streams, rivers, lakes, and oceans, and infiltrating underground to form groundwater. This water-recycling system works only as long as we do not overload it with wastes or withdraw water faster than it is replenished. In parts of the world, we are doing both of these things.

Differences in average annual precipitation play a large role in water availability. For example, Canada, with only 0.5 % of the world's people, has 20 % of the world's fresh water. In comparison, China, with 21 % of the world's people, has only 7 % of the world's fresh water. Approximately 1.4 billion people around the world lack access to clean water. Inadequate access to clean water claims the lives of millions, many of them children, due to water-borne diseases and poor sanitation. A growing world population, combined with dwindling water resources, will compound this problem. We are using more than half of the world's available surface runoff and fresh water for irrigating crops, cooling power plants, running industries, and satisfying our home and public consumption needs. This percentage is expected to increase to 70 %, or even 90 %, by 2025. By then, it is estimated that one-third of the world population will be facing a severe water crisis.

Water Pollution

There are many causes of water pollution, including agricultural runoff, sewage and wastewater, industrial waste, atmospheric deposition, marine dumping, oil pollution, and radioactive waste. Agricultural runoff sends chemicals from pesticides, fertilizers, and feedlots into the water supply (**Figure 10(a)**). Sewage disposal is a major problem in developing countries, since many people in these areas do not have access to sanitary conditions and clean water. It can also be a problem in developed countries. For example, in some large Canadian cities, the water is not treated and raw sewage is discharged into waterways as overflow during storms. Many industrial facilities use fresh water to carry waste into rivers, lakes, and oceans. Pollutants from industrial sources can include asbestos, lead, nitrates, phosphates, mercury, and petrochemicals.

Atmospheric deposition is the pollution of water caused by air pollution. Water particles mix with carbon dioxide, sulfur dioxide, and nitrogen oxides, forming a weak acid. This acid returns to the water cycle as acid rain, polluting groundwater and marine habitats.

Litter being dumped in the ocean is becoming an increasingly serious problem. The Great Pacific Garbage Patch is an "island of garbage" that has been caught in the ocean current in the central North Pacific Ocean. It is composed mainly of plastics, chemical sludge, and other debris. It extends over an indeterminate area, with estimates ranging widely, depending on the degree of plastic concentration that is used to define the affected area. Ocean garbage and debris can cause problems for marine animals and may result in their death (**Figure 10(b)**).

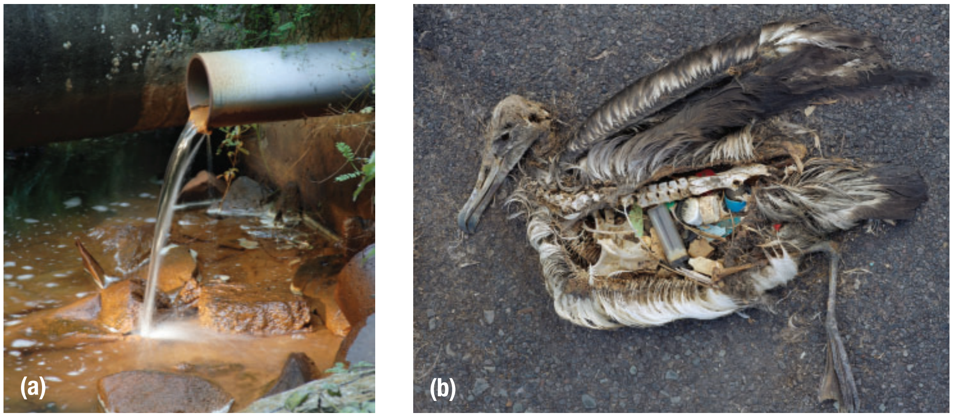


Figure 10 (a) Fertilizers and pesticides from agriculture and industrial waste can pollute waterways. (b) This albatross died from eating plastic floating in an ocean.

Oceans are also polluted by oil from oil spills, routine shipping, runoff, and dumping. Oil spills from drilling accidents can pollute vast areas of ocean water, leaving a wake of destruction. This happened in the Gulf of Mexico in 2010, when the Deepwater Horizon oil platform exploded and leaked over 700 million litres of oil into the ocean, creating a slick with an area of more than 10 000 km^2.

Nuclear waste is produced from industrial, medical, and scientific processes that use radioactive material. Nuclear waste can have detrimental effects on marine habitats. Problems with nuclear power plants can cause intense pollution, as happened at Japan's Fukushima nuclear plant in 2011. An undersea earthquake and the resulting tsunami damaged the plant, causing radioactive particles to leak into the surface water and groundwater around the plant and to flow directly into the ocean. Particles were also vented into the air and likely rained down to contaminate crops and livestock. Seawater that was used to cool the reactor spread radiation to the ocean, effectively spreading radiation around the world.

We must conserve water, one of our most precious resources. As climate change continues, melting glaciers, prolonged droughts, and changing weather patterns could have an effect on the availability of water in ways that we have not yet considered.

Air Quality and Pollution

While we will never run out of air, the quality of the air we breathe is a significant concern. Yet, we pollute the atmosphere by burning fossil fuels, forests, and garbage. Other sources of air pollution include manufacturing emissions and gases released by livestock. Air pollution has a profound effect on climate. Gases that trap heat in the atmosphere are called greenhouse gases. Some greenhouse gases, such as carbon dioxide, occur naturally and are emitted to the atmosphere through natural processes and human activities. Other greenhouse gases are created and emitted solely through human activities. The principal greenhouse gases that enter the atmosphere because of human activities are carbon dioxide, methane, nitrous oxide, and fluorinated gases.

Climate change is the continuing rise in the average temperature of Earth's atmosphere and oceans. It is caused by increased concentrations of greenhouse gases in the atmosphere, resulting from human activities such as deforestation and the combustion of fossil fuels. Every kilowatt-hour (kWh) of electricity that is generated by burning coal produces about 0.8 kg of CO_2. Each litre of gasoline that is used emits 2.3 kg of CO_2 into the air.

Climate change is causing Earth's average temperature to increase, raising sea levels and changing the amount and pattern of precipitation. Warming in the Arctic will cause glacial retreat, as well as permafrost and sea ice melting, to continue (**Figure 11**). Other likely effects of climate change will include more frequent occurrence of extreme weather events, such as heat waves, droughts, and heavy rainfall. Species extinctions due to shifting climate zones will continue, and changes in agricultural yields will occur. Particulates, or tiny particles, from natural events, such as forest fires and volcanic eruptions, will also be added to the atmosphere and will compound the problem. Climate change impacts will vary from region to region around the world.

UNIT TASK BOOKMARK

In this section, you have learned about many environmental problems that have arisen as a result of interactions between humans and their environment. You may decide to select one problem as your topic for the Unit Task on page 688.

Figure 11 An iceberg calved from the Jakobshavn Isbræ (Glacier) in Greenland. This glacier has been studied for over 250 years, and has been an important source of information about climate change and how it affects icecaps.

Air pollution can create many health problems. Ground-level ozone, sulfur oxides, nitrous oxide, and airborne particulates can all aggravate respiratory illnesses, such as asthma. Many airborne chemicals have also been associated with low birth weight babies and infant lung infections. Studies are underway to investigate the effects of air pollution on babies while in the womb.

There are many ways that we can help to curb air pollution. On a large scale, cleaning up industrial emissions, as well as using greener energy sources, will reduce pollutants. On an individual basis, we can all try to burn less gasoline and use less electricity to reduce our global footprint.

Investigation 13.2.1

Populations and Consumption (p. 677)
You have learned how the choices you make can affect the natural environment and how humans and nature are connected. In this investigation, you will investigate the relationships between human consumption and Earth's resources.

13.2 Review

Summary

- The move from rural areas to urban areas had advantages for human populations, but it also required the development of more infrastructure and services, such as transportation and sanitation.
- The present food supply is adequate to feed all the people in the world, but food production and distribution are unequal worldwide.
- An energy pyramid shows the flow of energy between trophic levels.
- High-input agriculture uses resources such as water and electricity to produce food. Low-input agriculture requires only human and animal labour.
- Low-impact diets require less energy and reduce our ecological footprint.
- Agriculture is necessary to grow our food, but some of our agricultural techniques have a high impact on natural resources.
- Soil quality is threatened in many areas, leading to erosion and nutrient loss.
- Water is one of our most precious resources, yet it is not well protected. Water pollution comes from many sources, including agriculture, industry, and human waste.
- Air pollution has far-reaching effects, most significantly air quality and climate change.

Questions

1. Name some ways that the development of cities affects the environment. K/U
2. Suggest three ways that urban sprawl (cities pushing outward into rural areas to accommodate their ever-growing populations) affects the biosphere. K/U
3. (a) Compare and contrast industrialized agriculture and traditional agriculture.
   (b) Where and how is each type practised?
   (c) Give an example of each. K/U
4. What does it mean when we say that soil has lost its fertility? K/U
   (a) Suggest two ways to enhance soil fertility.
   (b) What are the downsides to these methods?
5. Aquaculture is becoming increasingly popular around the world. Research aquaculture and answer the following questions. 🌐 K/U T/I
   (a) What is aquaculture?
   (b) Canada has an abundant supply of wild fish. Why do we have aquaculture in Canada?
   (c) Where is aquaculture practised in Canada?
   (d) Are aquaculture organisms genetically modified? Explain.
6. Climate change is caused by an increased concentration of greenhouse gases in the atmosphere by both natural events and human activities. K/U T/I C A
   (a) How does deforestation contribute to climate change?
   (b) List some ways that humans are contributing to climate change.
   (c) Based on the list you made, how many of those activities are things you either do or are involved in? Suggest ways that you could reduce your personal carbon footprint.
7. It has been argued that the greatest threat to the future of the planet is not the high resource consumption in the developed world, but rather it is the resource consumption by the rapidly growing populations in developing parts of the world. Do you agree or disagree? 🌐 T/I C A
   (a) With a partner, discuss arguments and counter-arguments for each position. Use the Internet and other sources to assist you in the formulation of your positions.
   (b) Create a Plusses, Minuses, and Interesting/Implications (PMI) chart to summarize your thinking.

🌐 WEB LINK

13.3 Explore an Issue in Population Growth

Feeding a Growing Population

SKILLS MENU

- Defining the Issue
- Researching
- Identifying Alternatives
- Analyzing
- Defending a Decision
- Communicating
- Evaluating

Food, water, and a healthy environment are essential for the well-being of all people. The International Development Research Centre (IDRC) believes that these resources are also the building blocks for more sustainable and equitable development. However, these resources are threatened around the world, particularly in developing countries. Only one-third of the people in developing countries live on land that produces enough food to feed them. The rate of population growth makes this problem more urgent. Countries and regions with above-average population growth and inadequate agricultural support face a continuing challenge to provide a sufficient per capita food supply. Hunger is a complex issue, affected by factors other than just population growth and agricultural production. Social, economic, political, and climate factors also play key roles (**Figure 1**).

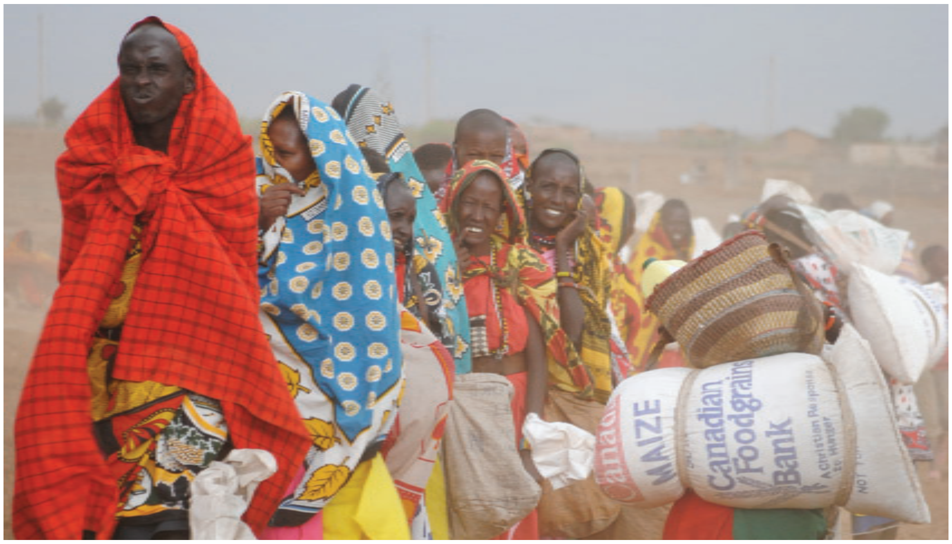


Figure 1 In 2011, an extreme drought in South Africa led to a famine that affected over 11 million people.

The Issue

According to the Canadian International Development Agency (CIDA), Canada's main government body for distributing overseas aid, Canadians are the largest per capita food aid donors in the world. Canada has a number of agencies and programs that are designed to support international development projects in both developed and developing countries, many of which are related to agriculture and food production. However, the Canadian government's Oversight Committee on International Development wants to know if Canada is actually playing an effective and significant enough role in helping to nourish the world's growing population. CAREER LINK

You have been asked to sit on an independent review panel to explore this issue. Each member of the panel (your group) will do independent research and then share her or his findings with the other members. A spokesperson for the panel will then present a summary of the findings and any recommendations to a government panel (your class), which will include the federal ministers for Agriculture and Agrifood, as well as representatives from the Canadian Wheat Board.

Goal

To research and evaluate one or more of Canada's agencies and programs for enhancing global food production

Research

SKILLS HANDBOOK A4

Use the Internet and other sources to investigate Canadian agencies and programs that are geared toward increasing global food production. Some possible agencies and programs to investigate are the International Development Research Centre (IDRC), the Canadian International Development Agency (CIDA), the Micronutrient Initiative, the Flour Fortification Initiative, World Vision Canada, Charity Village, and the Canadian Foodgrains Bank. Since it is important to consider all points of view when doing research, you should also investigate critical independent sources of information.

Consider the following questions. If you have other questions or concerns, consider them as well.

- What are the key agencies and programs? What are their short-term and long-term goals?
- How do they help? For example, do they help by providing food or by teaching agricultural techniques?
- In which parts of the world do they provide aid?
- What costs are associated with running the programs? How are the programs funded? Are they fully federally funded? Do they accept public donations? How much of the funding goes to aid programming? How much goes to administrative costs?
- What are the short-term and long-term benefits of the programs you investigated?
- What do critics say about these programs? WEB LINK

Possible Solutions

Based on your research, identify ways that the agencies and programs could be more effective or improve their current practices. Consider the following questions:

- Do you believe that Canada's international contributions to curbing world hunger are effective and/or significant? Why or why not?
- What recommendations would you make to improve Canada's involvement in feeding a growing world population?

Decision

Based on the information you gathered, determine the effectiveness of the agencies and programs, and compile a set of recommendations for the Oversight Committee.

Communicate

After you have completed your independent research, share your findings with the other members of the review panel. A spokesperson for the panel will then present a summary of the findings to the members of the government Oversight Committee.

Plan for **Action**

International Youth Programs

Global issues such as world hunger concern all of us. CIDA has an International Youth Internship program that provides opportunities for Canadians to increase their awareness, deepen their understanding, and engage in international development. Investigate this program and other global development programs that young people can become involved in.

1. Use the Internet and other sources to find out what programs are available.
2. What are the requirements and commitments for students who want to become involved?
3. Prepare a brief Plan for Action that outlines the specific activities you could become involved in and explains what your involvement would entail and how it would help Canada feed a growing world population.
4. Present your Plan for Action to your class, and consider putting your plan into action.

WEB LINK

Human Population: The Future

13.4

The rapid growth in the world population over the past two centuries has raised concerns that humans are beginning to overpopulate Earth, and that Earth may not be able to sustain an ever larger number of people. The demands of an increasing population increase the demands for natural resources, clean air, and water. Responding to the demands of a rapidly growing population can challenge a country's ability to manage its natural resources sustainably. For example, people may not be able to access clean, safe water because more and more households and industries are using increasing amounts of water. Deforestation may occur as trees are cut to provide building materials or land for grazing and agriculture. Desertification may occur as land that has been intensively farmed becomes depleted of its nutrients, causing once fertile land to no longer be arable. The air may become more polluted as vehicular traffic increases, people use more energy, and the world continues to industrialize. Many of Earth's resources are renewable. However, these resources are renewable only as long as they are not overused or polluted.

Supply and Demand

Earth's natural ecosystems provide all the species on the planet with food, water, shelter, and the ability to recycle naturally occurring wastes. However, resources are limited. There is only a certain amount of fresh water available. Photosynthesis only captures and stores a certain amount of carbon, and the rate of decomposition is limited by a variety of biotic and abiotic factors. Demands for available resources vary from species to species and change over time. As populations increase in size, their demands for resources also increase. In addition, as the standard of living increases, the per capita consumption rate increases, putting a further drain on resources. Two growing concerns are causing many individuals, corporations, and governments to reassess their use of natural resources. First, many resources, notably metals and fossil fuels, are possibly running out. Second, pollution and the degradation and conversion of land are reducing the renewal of resources.

The carrying capacity of Earth for humans is estimated to be around 10 to 15 billion people. What happens if we exceed it? In general, when a population exceeds its carrying capacity, two things usually happen: mortality rates increase and birth rates decrease, usually because the ecosystem is becoming degraded. According to the Global Footprint Network, we use the equivalent of 1.5 planets to provide the resources we use and to absorb our waste. This means that it now takes Earth one year and six months to regenerate what we use in one year. Even conservative models suggest that if current population and consumption trends continue, we will need the equivalent of two Earths to support us by the middle of this century. If we continue turning resources into wastes faster than wastes can be turned back into resources, we could end up in an **ecological deficit**.

Different ecosystems vary in their capacity to meet human needs. Earth's total **biocapacity** (its ability to produce biological materials that are useful to humans and to absorb the wastes that are created by humans) is dependent on the available biologically productive areas of land and water. Biocapacity is measured in units called global hectares. A global hectare (gha) represents one hectare of average biological productivity and waste-absorbing capacity. One actual hectare of tropical rainforest, for example, has a high biocapacity (about 3 gha) because it is much more productive than the average hectare on Earth. One hectare of desert has a biocapacity of less than 1 gha.

Biocapacity is dependent on natural conditions. It is also dependent on how the land is used; for example, if it is used for farming or forestry. Worldwide, biocapacity is not evenly distributed. According to the *Living Planet Report* in 2007, 10 countries held about 60 % of the world's biocapacity (**Figure 1**).

ecological deficit resource use and waste production that exceeds a sustainable level

biocapacity a measure of an ecosystem's ability to produce useful biological materials and to absorb waste materials created by humans

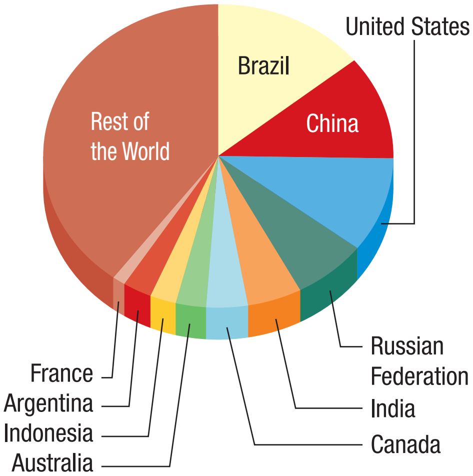


Figure 1 According to *The Living Planet Report*, 10 countries account for 60 % of the world's biocapacity, as of 2007.

The expressions "global hectare per person" or "biocapacity per person" refer to the amount of biologically productive land and water that is available per person on the planet (**Figure 2**). If land is degraded, then more land is needed to support each person and the biocapacity of Earth goes down. If technologies increase our ability to produce food in a sustainable manner, then Earth's biocapacity increases.

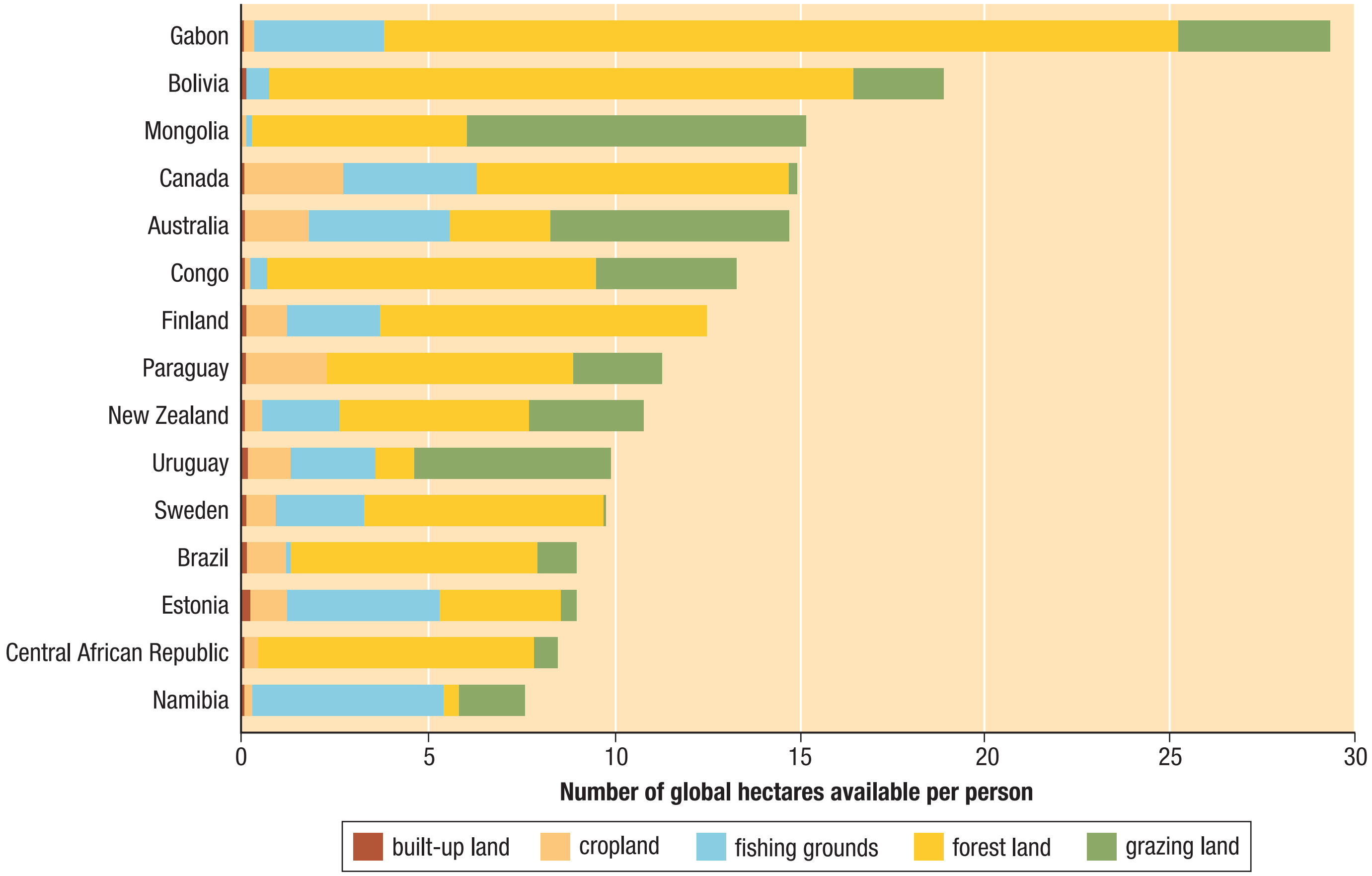


Figure 2 According to the *Living Planet Report*, the biocapacity per person is highest in Gabon. Look at the key to see what resources are most abundant in each country.

We need what nature provides, but how do we know how much we are using and how much we have available to use? The concept of the ecological footprint was developed at the University of British Columbia in 1990, and it is now used around the world to measure the human population's demands on nature. It measures the land and water area that a human population requires to produce the resources it consumes and to absorb its carbon dioxide emissions, using current technology.

The 2010 Province of Ontario's *Ecological Footprint and Biocapacity Analysis* states that, per capita, Ontario residents are placing some of the highest demands on the planet's resources. With an average ecological footprint of 8.4 gha (global hectares) per person in 2005, only three of 150 countries with reported ecological footprint data have a higher average per-person ecological footprint. In 2005, the average biocapacity in Ontario was 8.5 gha per person, just above the average Ontario ecological footprint. However, Ontario's biocapacity is substantially lower than the Canadian average of 20.0 ha per person. Ontario enjoys the benefits of a per capita biocapacity that is four times the world average that is available per person. This resource-intense lifestyle is not sustainable.

If our demand for resources, or ecological footprint, exceeds our biocapacity, there is an ecological deficit. Conversely, there is an ecological reserve if the biocapacity of a region exceeds its population's footprint. Today, we are living in an ecological deficit.

If we continue to use resources in the same manner, we will experience collapsing fisheries, deforestation, depletion of freshwater sources, and increasing carbon dioxide emissions. It is time for individuals and institutions worldwide to recognize our ecological limits.

Human Population Projections

No one can predict the future of the human population with any certainty, since assumptions that are made when creating projections may change. Some projections suggested that the world population would double in 40 years if human population growth continued at the same rate that it did in the last century. However, studies show that our population is not growing as quickly as it did during much of the twentieth century. The United Nations Development Program (UNDP) has released data on human fertility (the total number of births per woman) for 162 countries. Compared with 1970 to1975, 152 countries had lower human fertility in 2000 to 2005, three countries showed an increase in fertility, and seven countries showed no change (**Table 1**). Note that, while Finland has a consistent increase in total births per woman over the years, a country is considered to be growing only if its fertility rate exceeds 2.0. Also note that there was a slight increase in the birth rate in four developed countries in the period from 2005 to 2010.

Table 1 Human Development Index and Fertility Rate (Total Births per Woman): A Sample of UNDP Data for 162 Countries. Countries are ranked by their 2005–2010 fertility rate.

Country	Fertility rate, 1970–1975	Fertility rate, 2000–2005	Fertility rate, 2005–2010
Portugal	2.70	1.50	1.46
Canada	2.00	1.50	1.53
China	4.90	1.70	1.73
Finland	1.62	1.75	1.80
Norway	2.20	1.80	1.85
Brazil	4.70	2.30	1.90
United States	2.00	2.00	2.05
Indonesia	5.20	2.40	2.18
India	5.40	3.10	2.81
Democratic Republic of the Congo	6.29	6.70	6.10
Timor-Leste	6.15	6.96	6.50

Concerned about the global population and its effect on Earth, world leaders adopted the United Nations Millennium Development Goals in 2000, committing their nations to achieving the following goals by 2015:

- elimination of poverty and hunger
- universal education
- gender equality
- improved child health
- improved maternal health
- reduction in number of HIV/AIDS infections
- environmental sustainability
- global partnership

These goals can be achieved only if population growth is controlled. In 1994, the United Nations held an International Conference on Population and Development (ICPD), which set a target for global investment in family planning. As of 2004, the investment had fallen dramatically short of this target. Consequently, family planning information and devices (usually for fertility control) are not readily available in many of the lowest-income countries. In 1950, Sri Lanka and Afghanistan had the same population. Sri Lanka began strong efforts to make family planning available in culturally acceptable ways. This did not happen in Afghanistan. By 2050, Afghanistan will have four times as many people as Sri Lanka.

Meeting Human Demands while Conserving Biodiversity

Biodiversity, or the variety of life on Earth, is an important global issue. It is measured as the variety within species, the variety between species, and the variety of ecosystems. Humans, like all species, are dependent on the resources of Earth. Species and ecosystems renew our needed resources in many ways. They maintain oxygen in the atmosphere, remove carbon dioxide from the air, filter and purify water, pollinate plants, decompose wastes, and transfer nutrients.

However, our demand for food, water, and energy puts thousands of other species and ecosystems at risk. For example, birdwatchers and ornithologists who have counted and monitored the behaviour and activity of bird populations have observed that they are affected by the loss of habitats as cities and towns expand into adjoining land. Birds also lose habitats when agricultural operations expand to increase productivity. Birds that make annual migrations from temperate areas of the world to tropical and subtropical areas must survive changes across their entire route of habitats, each of which is essential to their survival.

Drylands are arid, semi-arid, and sub-humid areas where precipitation is scarce and more or less unpredictable. Drylands cover approximately 41 % of Earth's land surface and are home to about 38 % of the human population. However, between 10 and 20 % of the drylands are subject to some form of severe land degradation, directly affecting the lives of at least 250 million people. Climate change, combined with increasing pressure on water resources for these people and their crops and animals, compounds the problems that confront them.

A changing climate will alter a country's biodiversity. Scientists estimate that about 10 % of the world's known species will be at an increasingly higher risk of extinction for every 1 °C rise in temperature. Some species will adjust or adapt to changing conditions, but others will not. Some species, such as the moose, will have to move farther north as the southern edge of their range gets warmer. Migratory birds may return earlier in the spring and stay longer in the fall. Decreased ice cover and changes to times when waterways freeze or thaw may affect the food supply for aquatic life and interfere with fish spawning. Currently, over 500 plant and animal species are considered at risk in Canada, and recovery activities are being undertaken to ensure that 200 other species do not become endangered. All species, including humans, depend on each other to survive. Many human activities impact the survival of other species. There are examples of this throughout the world. In tropical regions, for example, vertebrate populations have declined by 60 % in the last 40 years, according to the *Living Planet Report*. Much of this decline is due to changes in land use and deforestation (**Figure 3**).

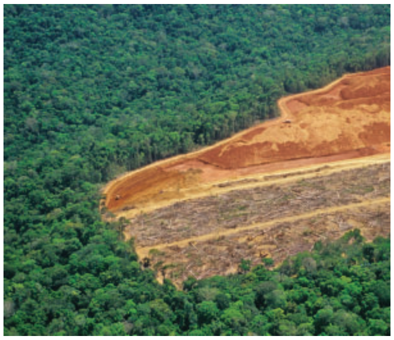


Figure 3 Deforestation for agriculture and wood products, especially in tropical areas, has huge environmental impacts, including loss of biodiversity.

The 2006 IUCN list of threatened species shows that, worldwide, 1141 mammals, 1222 birds, 423 reptiles, 1905 amphibians, 305 crustaceans, and 424 insects are categorized as extinct, extinct in the wild, critical, endangered, or vulnerable. More research is needed to gain a better understanding of the world's biodiversity before it is lost.

Making changes in our approach to conservation means identifying the root causes of the loss of biodiversity and the factors that are impeding conservation (**Figure 4**). It also means changing our own lifestyle, the food we eat, and our use of energy. We must learn how to protect Earth's ecosystems and resources while meeting our own needs. The survival of countless species around the globe—including our own—depends on our stewardship of the planet.

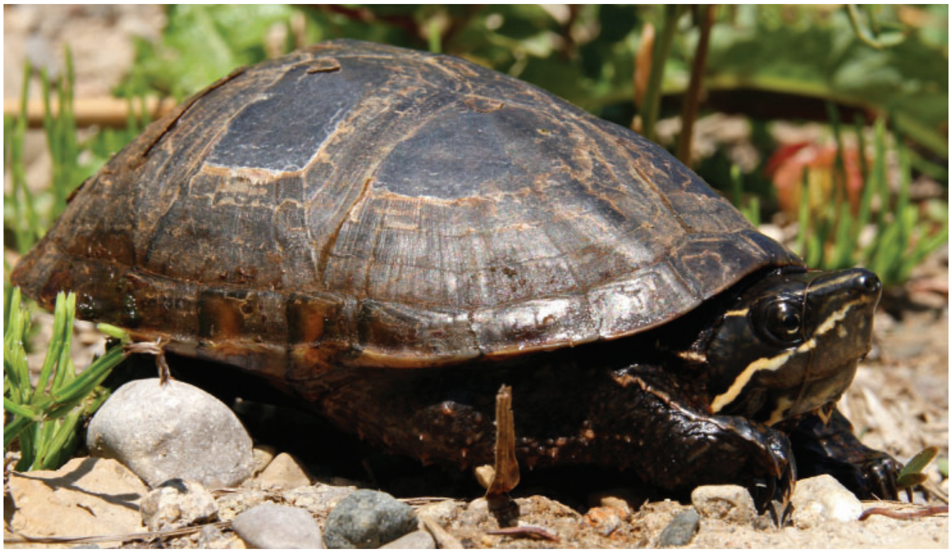


Figure 4 Land development and the draining of wetlands significantly affect the biodiversity of those ecosystems. The stinkpot turtle lives in waterways and wetlands in southern Ontario. Much of its habitat has been destroyed by shoreline development, and it is now listed as a threatened species in Ontario. The turtle gets its name from the musky fluid it emits when it feels threatened. Conservation efforts are underway, including research studies and a shoreline restoration project in St. Lawrence Islands National Park.

Taking Action

How can we make a difference? There are many examples of ways that people are already making a difference. Green buildings are becoming more common in many countries. There are office buildings, factories, and schools that use natural light, recycle wastewater, are powered by solar energy, have recycled-content decor, and are built near public transportation. City planners are designing sustainable neighbourhoods, with services within walking distance of the homes, and incorporating vertical farming techniques by including skyfarms in cities. E-books are increasingly taking the place of paper books, saving our trees. Power companies now offer alternatives to non-renewable resources. Solar panels, wind turbines, hydroelectricity, and green natural gas with net-zero carbon dioxide emissions are available. Even car companies are making more hybrid models and all-electric vehicles to save or avoid the use of gasoline and reduce greenhouse gas emissions. While these technologies are not yet widespread, they are more popular now than they were a decade ago, and this trend will likely continue.

It is up to us—as individuals, as local groups, and as a global community—to re-think how we live in order to make a difference. In the meantime, we must encourage others to do the same. Respect the rights of others. Use education and training to become informed. Learn to be objective and to examine and evaluate data or evidence. We have seen that action is needed at both the species and habitat levels, but there is a propensity to focus more on the species level.

The science of biology can be at the centre of the movement to conserve biodiversity, while guiding our efforts to achieve sustainable use of the resources we need. Conservation begins at home, whether protecting local habitats and species or protecting ecosystems.

UNIT TASK **BOOKMARK**

You may consider how you would take action to reduce the impact of the environmental issue you selected for the Unit Task on page 688.

Investigation **13.4.1**

Comparing Ecological Footprints and Biocapacity (p. 679)
You have learned how consumption by a growing human population is affecting the supply of natural resources. In this investigation, you will examine how population, wealth, and other factors affect the size of our ecological footprint, and how this, in turn, affects Earth's biocapacity.

13.4 Review

Summary

- The effects of the consumption of an ever-increasing human population are overburdening Earth's natural resources.
- Biocapacity is the capacity of an area to provide biological resources and absorb wastes.
- The ecological footprint measures all the biological materials that are consumed and the carbon dioxide emissions that are released over the period of a year. It can be calculated for an individual, a community, or a country.
- Earth's biodiversity is threatened by the demands of the human population.
- As a global community, we need to safeguard and enhance our biodiversity through conservation and sustainable practices.

Questions

1. Using print or electronic sources, find a fact-based article about human population growth. Use the article to answer the following questions. Attach a copy of the article to your answers. 🌐 T/I C
   (a) In one sentence, describe the key concept of the article.
   (b) List five scientific facts in the article.
   (c) Write a one- or two-paragraph overview of the article in your own words.
   (d) Explain, in a paragraph, why the article is relevant today.
   (e) List at least two questions that you still had after you read the article.
2. Every year, Canada has an ecological "budget." For many years, we have exceeded our budget before the year is up. Use the Internet to answer the following questions. 🌐 T/I
   (a) What is ecological overshoot?
   (b) What is Earth Overshoot Day?
   (c) How is Earth Overshoot Day calculated? When was it (or will it be) this year?
   (d) Why is Earth Overshoot Day important?
3. How much biocapacity do you need to support your lifestyle? 🌐 T/I
   (a) Calculate your personal ecological footprint using a Personal Footprint calculator.
   (b) What can you do to reduce your ecological footprint?
   (c) How does your ecological footprint compare with the provincial average?
4. Research and describe the Aboriginal perspective on the environment and stewardship. Identify possible solutions, from the Aboriginal perspective, to any of the issues identified in this section. 🌐 T/I
5. How can we calculate the social and environmental well-being of an individual, a family, a community, or a province? 🌐 T/I
   (a) Use the Internet to find out what is meant by the Genuine Progress Indicator (GPI).
   (b) What does the GPI measure?
   (c) How does the GPI compare with the traditional measurement, Gross Domestic Product (GDP)?
   (d) How does the GPI help governments measure the quality of life in a given country?
6. Catastrophic losses of life have occurred many times in human history, yet few have had a significant impact on population growth. Since the fourteenth century, when the bubonic plague killed an estimated 75 million people in a global population of approximately 350 million, we have experienced continuous population growth. One event, however, is believed to have had a major impact on the world population. Research the outcome of the Toba super-eruption, recognized as one of the world's largest known volcanic eruptions. 🌐 T/I
   (a) Describe the time, location, and overall impact of this super-eruption.
   (b) Describe volcanic winter and cooling.
   (c) What is the genetic bottleneck theory, and how does it apply to this super-eruption?
   (d) Several populations are believed to have survived. Where did these populations live, and what scenario has been proposed to explain how they went on to re-populate Earth?
   (e) Why do the large losses of life that occur today have so little effect on the world population?

🌐 WEB LINK

13.5 Biology JOURNAL

The Living Planet Report

SKILLS HANDBOOK A3

ABSTRACT

Every two years, the World Wide Fund for Nature (WWF) and its partner organizations, The Zoological Society of London and the Global Footprint Network, publish *The Living Planet Report*. This report describes the changing state of biodiversity and explains how the human consumption of natural resources affects our biosphere. It is a major scientific undertaking, monitoring changes in 7953 populations of 2544 species. The most recent report confirms that we are experiencing an ecological deficit. Canada's ecological footprint is ranked as the seventh largest per capita among the 130 nations studied. Governments, industry, and individuals in Canada and around the world need to work aggressively to reduce their ecological footprint. Failure to do so could result in permanent loss of biodiversity and erode Earth's ability to support life adequately.

Introduction

For many years, we have known that air and water pollution, habitat loss, and greenhouse gas emissions are a concern, but how do we actually measure the impact of these activities on a global scale? The scientists who compiled *The Living Planet Report* have attempted to do just that. In cooperation with the scientific community, the report explores the issues and problems that we face today and considers the potential solutions. The key finding of the 2010 report is clear: the demands of humans exceed the capacity of the planet. We want and use more than we can have.

Method

Scientists used two indicators to measure the health of the planet: the Living Planet Index (LPI) and the Global Footprint. The LPI measures changes in the health of Earth's ecosystems by tracking the trends of 7953 populations of 2544 vertebrate species. The LPI for the 2010 report was calculated using species population data from scientific journals and literature that covered the period from 1970 to 2007. Annual data points were interpolated using a mathematical model to calculate the average rate of change each year across all species. The average annual rates of change over all the years were put together to create the index, with the year 1970 set as year one.

The ecological footprint is a scorecard that looks at human consumption of the following resources: grazing land, forest, fishing grounds, cropland, and builtup land. It also looks at our CO_2 emissions, based on the area of trees required to absorb the amount of CO_2 we create. As well, it calculates our water footprint, which is the volume of fresh water used by people. We use water for drinking, washing, bathing, and producing food and goods. Less than 1 % of the world's fresh water is available to us for consumption, and this amount is dwindling, especially as climate change causes glaciers to shrink and weather patterns to change.

Footprint calculations are very complex, taking into account the land and water that are needed to support human life, in hectares per person, and analyzing the production and consumption of each country per year. Linking the global footprint to our biocapacity gives us a clear indication of our impact on the planet.

Findings

The Living Planet Report shows that humans are consistently demanding more from the planet than it can provide. The global LPI has been declining consistently since the 1970s, with a 30 % drop in the number of vertebrate species between 1970 and 2007 (**Figure 1**). WEB LINK

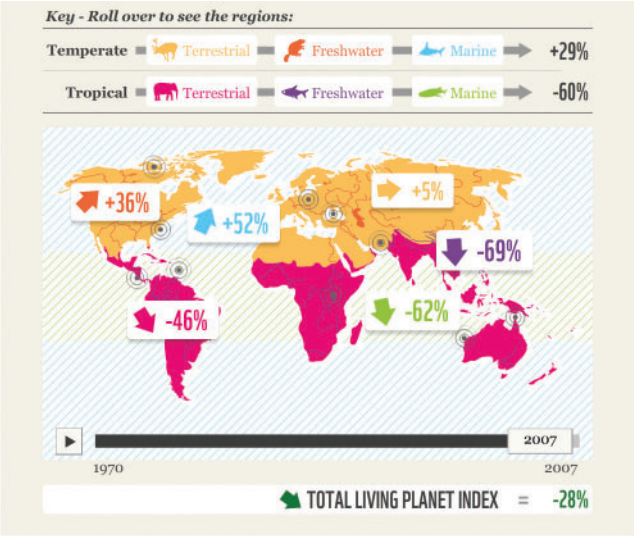


Figure 1 The change in the Living Planet Index between 1970 and 2007: Positive numbers mean that biodiversity is increasing, and negative numbers mean that it is decreasing.

The Living Planet Report also showed that the size of our ecological footprint has doubled since the 1960s. In fact, in 2007, our footprint exceeded Earth's capacity to renew resources by 50 %. The size of a country's ecological footprint depends on its wealth and the size of its population, as well as the availability of its resources (**Figure 2**). Canada's ecological footprint ranked as the seventh largest per capita among the 130 nations studied. WEB LINK

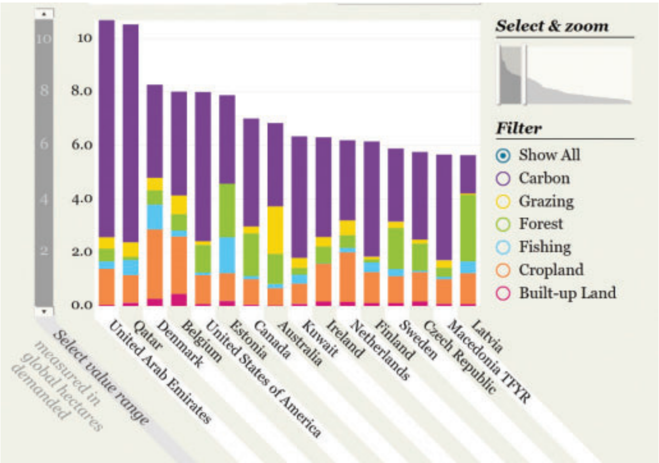


Figure 2 Contributors to the global ecological footprint, based on CO_2 output and impact on forests, fishing areas, cropland, range lands, and urban development

Discussion

Our growing human population is perhaps the biggest concern that the report raises. In 2010, the world population was just under 7 billion. By 2050, according to estimates, there will be 9 billion people on the planet. This change in population will further increase our demand for natural resources. If we do not change how we use our natural resources, the WWF believes that we will need the equivalent of two Earths to meet our annual demands by 2030. If we change our ways, however, we could reduce our impact on the natural world and live more sustainably.

The Living Planet Report suggests six ways that we can move toward positive change and create a green economy:

- better measure our well-being (change our ideas of wealth and prosperity to better reflect the world in which we live)
- invest in nature (be realistic about the cost of natural resources)
- reduce and better manage our food and energy demands
- manage our land and sea resources
- share our energy, food, and water in an equitable way with other countries that have less
- improve governance in industry, as well as politics

Investing in good stewardship of our natural resources will help us shift to a greener economy. More sustainable agriculture, better management of land and aquatic resources, and the willingness to share these resources will help to create a healthy future for everyone.

Further Reading

Collen, B., McRae, L., Kothari, G., Mellor, R., Daniel, O., Greenwood, A., Amin, R., Holbrook, S. & Baillie, J. (2008) Living Planet Index. In J. Loh (Ed.), *2010 and Beyond: Rising to the Biodiversity Challenge*. Gland, Switzerland: WWF International.

McRae, L., Loh, J., Collen, B., Holbrook, S., Amin, R., Latham, J., Tranquilli, S., & Baillie, J. (2007). Living Planet Index. In S. Mitchell and A. Peller (Eds.), *Canadian Living Planet Report 2007.* Toronto: WWF-Canada.

WWF, *The Living Planet Report* (2010). Available online at World Wide Fund for Nature.

WEB LINK

13.5 Questions

Using the information in *The Living Planet Report*, answer the following questions.

1. (a) List five countries with an ecological footprint that is less than their biocapacity (ecological creditors).
   (b) Why do you think these countries live within their biocapacity? Explain.
   (c) Where are most of these countries located? T/I
2. Suggest ways that we could begin to redefine the meaning of a good lifestyle, which is in line with the thinking of a green economy. T/I A
3. (a) List five countries with an ecological footprint that is greater than their biocapacity (ecological debtors).
   (b) Why do you think these countries live beyond their biocapacity? Explain.
   (c) Where are most of these countries located? T/I
4. What do critics say about the findings of *The Living Planet Report*? What do the creators of the ecological footprint say about the findings? T/I

WEB LINK

Investigation 13.2.1 CORRELATIONAL STUDY

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Populations and Consumption

Like all other species, humans interact with the surrounding environment and consume resources. However, unlike most other species, humans produce wastes that do not degrade. As well, we consume energy, burn fossil fuels, and produce greenhouse gas emissions. We alter or replace entire natural habitats with urban developments and cropland, and we use increasing amounts of fresh water and mineral resources.

Correlational studies are used to look for relationships between variables. The correlation coefficient (r) is a measure of correlation strength. There are three possible results of a correlational study: a positive correlation ($r > 0$), a negative correlation ($r < 0$), and no correlation ($r = 0$). If r is close to 0, there is no relationship between the variables. If r is positive, as one variable gets larger, the other variable gets larger. If r is negative, as one variable gets larger, the other variable gets smaller.

The Pearson Product-Moment correlation technique, which you will use in this investigation, works best with linear relationships. In a linear relationship, as one variable gets larger, the other variable gets larger or smaller in direct proportion. While a correlational study can suggest that there is a relationship between two variables, it cannot prove that one variable causes a change in another variable.

Purpose

SKILLS HANDBOOK A2.3

In this investigation, you will perform a correlational study to assess the relationship between population demographics and consumption.

Variables

You will consider the following demographic variables in this investigation:

- population size
- gross domestic product (per capita)
- gross national income (per capita)
- average years of formal schooling

You will also consider the following consumption variables:

- energy use
- CO_2 emissions
- meat consumed
- water use

Equipment and Materials

- data sets (**Table 1** and **Table 2**)
- spreadsheet or graphing software
- computer with Internet access

Table 1 Demographic Data

Country	Population	Gross domestic product ($/capita)	Gross national income ($/capita)	Average years of formal schooling
Australia	21 874 900	39 699	19 213.50	20
Brazil	193 773 800	11 239	2 842.36	14
Canada	32 271 000	39 057	20 789.50	16
India	1 134 403 000	3 339	441.56	10
Nigeria	134 728 890	2 422	288.37	9
People's Republic of China	1 331 460 000	7 519	865.03	12
United States	307 006 550	47 284	33 070.30	16

Table 2 Consumption Data

Country	Energy use (kg/person/year)	CO_2 emissions (tonnes/person/year)	Meat consumed (kg/person/year)	Water use (m^3/person/year)
Australia	5723.3	17.1	122.7	1149
Brazil	1067.6	1.9	82.4	305.4
Canada	8300.7	16.7	108.1	1468
India	512.4	1.1	5.2	644.1
Nigeria	776.9	0.7	8.6	78.67
People's Republic of China	1138.3	2.7	52.4	414.6
United States	7794.8	19.4	124.8	1550

Procedure

1. Choose a demographic variable from Table 1 and a consumption variable from Table 2.
2. Enter the data for both variables into your spreadsheet or graphing software in two columns. (Include the data for all the countries.) Determine the Pearson Product-Moment (linear) correlation coefficient for the two variables.
3. Record your findings.
4. Repeat Steps 1 to 4 for at least two other pairs of variables.

Analyze and Evaluate

(a) Why was this study designed as a correlational study rather than a controlled experiment? What are the strengths and limitations of a correlational study? T/I

(b) What was the correlation coefficient (*r* value) for each pair of variables? Which variables were positively correlated? Which were negatively correlated? Were any not correlated? T/I

(c) Did any of your findings surprise you? Why? T/I

(d) Suggest possible explanations for your findings. T/I

(e) The average life expectancies for the same countries are given in **Table 3**. T/I

Table 3 Life Expectancy Data

Country	Life expectancy (years)
Australia	81.54
Brazil	72.64
Canada	81.22
India	64.05
Nigeria	48.14
People's Republic of China	73.31
United States	78.66

(i) If you examined the relationship between life expectancy and consumption (Table 2), what kind of a correlation would you expect to find? Why?

(ii) Run your data to see if your predictions are correct. Do your results surprise you?

Apply and Extend

(f) Go online to gather similar data for different developed and developing countries. Determine the linear correlation for your new data sets. How do your findings compare with your previous findings? T/I

(g) Do all wealthy countries have consistently high rates of resource consumption? Use the Internet to research this question. T/I

WEB LINK

Investigation 13.4.1 OBSERVATIONAL STUDY

Comparing Ecological Footprints and Biocapacity

SKILLS MENU

- Questioning
- Researching
- Hypothesizing
- Predicting
- Planning
- Controlling Variables
- Performing
- Observing
- Analyzing
- Evaluating
- Communicating

Our ecological footprint tracks our demands on the biosphere by comparing these demands against the regenerative capacity of the planet. Every person has an ecological footprint, as do communities, countries, and the global population. The ecological footprint considers the following criteria:

- our use of range land, cropland, and forestry resources
- the fish we extract
- the amount of built-up land
- the amount of CO_2 that is absorbed by vegetation

Biocapacity is the ability of a natural area to provide products and services to humans. Water supply, forests, clean air, and available agricultural land are part of Earth's biocapacity.

Ecological footprint and biocapacity are related. Our ecological footprint is "demand," while Earth's biocapacity is "supply." There are many trends that influence the size of the ecological footprint of an individual, a community, or a country. A country's ecological footprint helps to determine its biocapacity.

In this investigation, you will see how population, wealth, and other factors affect the size of our ecological footprint, and how this, in turn, affects Earth's biocapacity.

Purpose

In this investigation, you will use the Ecological Footprint Atlas to compare Canada's ecological footprint with the ecological footprints of three other countries. Then you will determine global trends in Earth's biocapacity.

Equipment and Materials

- Ecological Footprint Atlas

Procedure

SKILLS HANDBOOK A2.4

1. Examine the data tables in the Ecological Footprint Atlas. Then compare the data for Canada with the data for three other countries:
   - one with a high ecological footprint (above 7)
   - one with a medium footprint (2 to 5)
   - one with a low footprint (below 2)
2. Compare the ecological footprint, biocapacity, and net exports of the four countries.

Analyze and Evaluate

(a) Compare the ecological footprints of the four countries. How do they compare? How does Canada's ecological footprint compare with the ecological footprint of each of the other countries? T/I

(b) What is the relationship between ecological footprint and biocapacity? T/I

(c) When did the human ecological footprint overshoot Earth's biocapacity? What are the implications of this? K/U A

(d) How did your results compare with your classmates' results? T/I

Apply and Extend

(e) Investigate the methodology behind the data in the Ecological Footprint Atlas. How were the data gathered? T/I

(f) Investigate your own ecological footprint. What can you do to minimize your personal impact on the planet? A

(g) Investigate countries with a high income but a low ecological footprint. How do you account for their low impact on the planet? T/I A

WEB LINK

CHAPTER 13 SUMMARY

Summary Questions

1. Create a study guide based on the Key Concepts in the margin on page 640. For each point, create three or four sub-points that provide further information, relevant examples, explanatory diagrams, or general equations.
2. Look back at the Starting Points questions on page 640. Answer these questions again, based on what you have learned in this chapter. Compare your answers with the answers you wrote at the beginning of this chapter. How have your answers changed?

Vocabulary

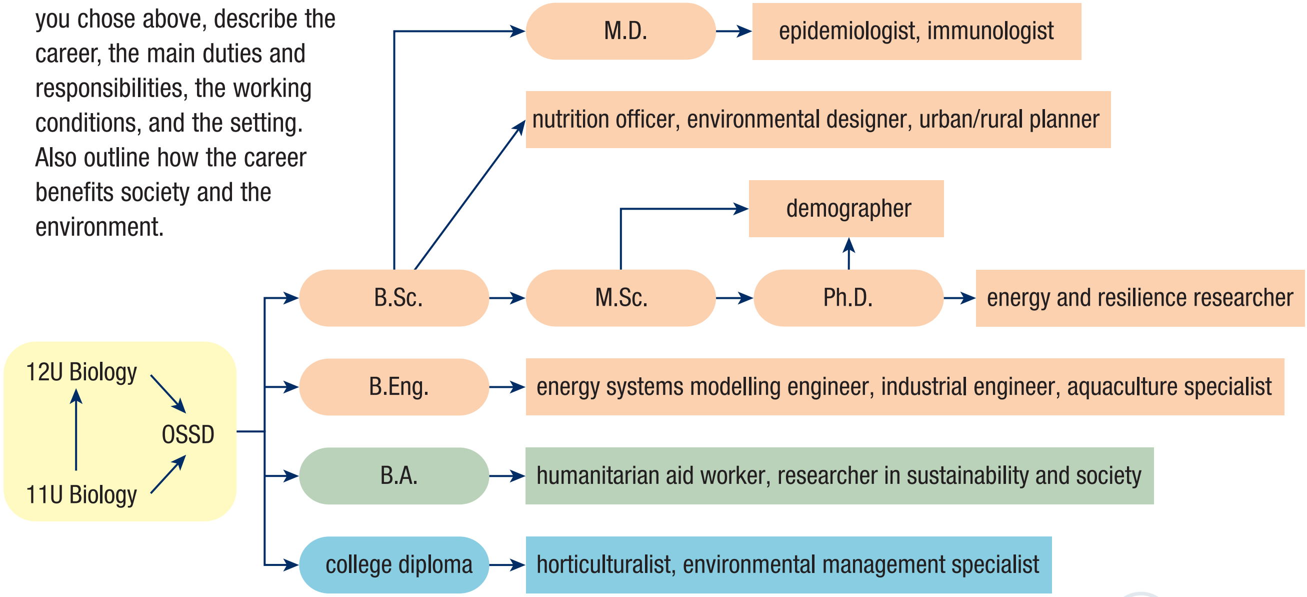
ecological footprint (p. 642)
pathogen (p. 644)
epidemic (p. 644)
Industrial Revolution (p. 645)
vaccine (p. 646)
population pyramid (p. 647)
Aboriginal peoples (p. 648)
demographic transition model (p. 650)
replacement rate (p. 651)
malnutrition (p. 655)
industrialized agriculture (p. 656)
traditional agriculture (p. 656)
energy pyramid (p. 658)
trophic level (p. 658)
salinization (p. 659)
sustainable or low-input agriculture (p. 660)
organic agriculture (p. 660)
bycatch (p. 661)
aquaculture (p. 661)
ecological deficit (p. 669)
biocapacity (p. 669)

CAREER PATHWAYS

SKILLS HANDBOOK A6

Grade 12 Biology can lead to a wide range of careers. Some require a college diploma or a B.Sc. degree. Others require specialized or post-graduate degrees. This graphic organizer shows a few pathways to careers mentioned in this chapter.

1. Select two careers related to human population dynamics that you find interesting. Research the educational pathways that you would need to follow to pursue these careers. What is involved in the required educational programs? Prepare a brief report of your findings.
2. For one of the two careers that you chose above, describe the career, the main duties and responsibilities, the working conditions, and the setting. Also outline how the career benefits society and the environment.


M.D.
epidemiologist, immunologist
nutrition officer, environmental designer, urban/rural planner
demographer
B.Sc.
M.Sc.
Ph.D.
energy and resilience researcher
12U Biology
OSSD
11U Biology
B.Eng.
energy systems modelling engineer, industrial engineer, aquaculture specialist
B.A.
humanitarian aid worker, researcher in sustainability and society
college diploma
horticulturalist, environmental management specialist

CAREER LINK

CHAPTER 13 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which term refers to the study of human populations? (13.1) K/U
   (a) ecology
   (b) geography
   (c) demography
   (d) biology
2. Which term refers to agents that cause infectious diseases? (13.1) K/U
   (a) pathogens
   (b) epidemics
   (c) immunity
   (d) pandemics
3. What percentage of Canadians now live in urban centres? (13.2) K/U
   (a) 50 %
   (b) 60 %
   (c) 70 %
   (d) 80 %
4. Which term refers to a type of agriculture in which food is grown using machines and commercial fertilizers and pesticides? (13.2) K/U
   (a) traditional agriculture
   (b) industrialized agriculture
   (c) sustainable agriculture
   (d) organic agriculture
5. What is bycatch? (13.2) K/U
   (a) the targeted species of fish
   (b) fish and shellfish that are raised for crops
   (c) fish that have been overharvested in conventional fisheries
   (d) species of fish that are captured due to their proximity to the targeted species
6. Which of the following best describes an ecological footprint? (13.2) K/U
   (a) amount of carbon dioxide emitted due to the consumption of fossil fuels by a particular person or group
   (b) measure of the area of land needed to produce food for one person
   (c) measure of the land and water required and pollution created by our demand for natural resources
   (d) amount of resources used that exceeds a sustainable level
7. Which of the following is the best definition of ecological deficit? (13.4) K/U
   (a) resource use and waste production that are below a sustainable level
   (b) naturally occurring substances that cannot be replenished by natural processes
   (c) ability of an ecosystem to produce useful biological materials
   (d) resource use and waste production that exceeds a sustainable level
8. Which of the following best describes biocapacity? (13.4) K/U
   (a) increasing concentration of a substance, such as a toxic chemical, in the tissues of organisms at successively higher levels in a food chain
   (b) measure of the ability of an ecosystem to produce useful biological materials and to absorb the waste materials produced
   (c) transformation of a substance into new compounds through biochemical reactions or the actions of micro-organisms, such as bacteria
   (d) use of biological agents, such as bacteria or plants, to remove or neutralize contaminants, such as those found in polluted soil or water

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

9. Advancements in science, technology, and medicine have led to an increased mortality rate. (13.1) K/U
10. The relationship between the population growth and economic development of many countries can be represented by the demographic transition model. (13.1) K/U
11. The present food supply is inadequate to feed all the people in the world. (13.2) K/U
12. Low-impact diets require more energy and increase our ecological footprint. (13.2) K/U
13. Water is one of our most precious resources, yet it is not well protected. (13.2) K/U
14. Air pollution has far-reaching effects, most significantly on air quality and climate change. (13.2) K/U
15. Geographic capacity is the capacity of an area to provide biological resources and absorb waste. (13.4) K/U
16. Earth's biodiversity is threatened by the demands of pollution. (13.4) K/U
17. An ecological footprint is calculated on a family basis. (13.4) K/U

Go to Nelson Science for an online self-quiz.

WEB LINK

Knowledge

For each question, select the best answer from the four alternatives.

1. What is currently the approximate total human population? (13.1) K/U
   (a) 9 billion
   (b) 7 billion
   (c) 6 billion
   (d) 5 billion
2. Which of the following best describes the advantages of the domestication of another species for humans? (13.1) K/U
   (a) decreased access to food, labour, and chemicals for treating disorders or controlling pests
   (b) increased access to food and to chemicals for treating disorders or controlling pests
   (c) increased access to food, labour, materials for constructing things, and chemicals for treating disorders or controlling pests
   (d) decreased access to food, labour, materials for constructing things, and chemicals for treating disorders or controlling pests
3. Which of the following needs to happen for zero population growth to be achieved? (13.1) K/U
   (a) Mortality needs to increase.
   (b) Mortality needs to decrease.
   (c) The replacement rate needs to be just higher than two children per couple.
   (d) The replacement rate needs to be just lower than two children per couple.
4. Why did urban migration occur? (13.2) K/U
   (a) The industrialization of agriculture positively affected the economy of small- and middle-sized farms.
   (b) Farming is independent of environmental conditions and is stable.
   (c) The rural labour market increased.
   (d) The industrialization of agriculture negatively affected small- and middle-sized farms.
5. Which conditions are optimal for agriculture in Canada? (13.2) K/U
   (a) dry conditions, warm temperatures, and rocky soil
   (b) dry conditions, seasonal temperatures, and optimum soil
   (c) wet conditions, warm temperatures, and rocky soil
   (d) wet conditions, seasonal temperatures, and optimum soil
6. Which country is the fourth-largest exporter of food? (13.2) K/U
   (a) United States
   (b) China
   (c) Russia
   (d) Canada
7. Historically, how have people obtained food? (13.2) K/U
   (a) agriculture and fishing
   (b) agriculture and aquaculture
   (c) agriculture, and hunting and gathering
   (d) agriculture and ranching
8. Desertification occurs when the productive potential of arid or semi-arid land
   (a) falls by 10 % or more because of natural climate changes and human activities
   (b) falls by less than 10 % because of natural climate changes and human activities
   (c) falls by 10 % or more because of natural climate changes
   (d) falls by 10 % or more because of human activities (13.2) K/U
9. At this time, what percentage of the world's available surface runoff and fresh water are being used for irrigation of crops, power plant cooling, industry, and home and public consumption? (13.2) K/U
   (a) 50 %
   (b) 70 %
   (c) 80 %
   (d) 90 %
10. Which of the following is considered to be a principal greenhouse gas? (13.2) K/U
    (a) carbon monoxide
    (b) carbon tetrachloride
    (c) carbon dioxide
    (d) ozone
11. Which of the following best describes what happens when a population exceeds its carrying capacity? (13.4) K/U
    (a) The mortality rate increases, and the birth rate decreases.
    (b) The mortality rate increases, and the birth rate increases.
    (c) The mortality rate decreases, and the birth rate increases.
    (d) The mortality rate decreases, and the birth rate decreases.

12. Which of the following best describes biocapacity? (13.4) K/U
    (a) careful observation and analysis of the geographic distribution of organisms
    (b) use of organisms, usually bacteria, to detoxify a polluted environment, such as an oil spill site or contaminated soil
    (c) maximum rate that a population can increase under ideal conditions
    (d) measure of the ability of an ecosystem to produce useful biological materials and absorb the waste products generated by humans

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

13. Due to advances in technology and social services, births now exceed deaths in many countries. (13.1) K/U
14. The demographic transition model accurately predicts the future of developing nations. (13.1) K/U
15. The domestication of animals contributed to the spread of pathogens, as diseases jumped from humans to animal populations. (13.1) K/U
16. The Industrial Revolution had a profound effect on the socioeconomic and cultural conditions of the time. (13.1) K/U
17. Safe drinking water is still not accessible to all Canadians. (13.2) K/U
18. Much of Canada is too hot, dry, or rocky, and/or lacks adequate soil for growing crops. (13.2) K/U
19. Land degradation occurs when natural or human-induced processes decrease the future ability of the land to support crops, livestock, or wild species. (13.2) K/U
20. Some large Canadian cities discharge raw sewage into waterways during storms as overflow. (13.2) K/U
21. If we continue to turn resources into waste products faster than waste products can be turned back into resources, we could end up in an ecological deficit. (13.4) K/U
22. If land is degraded, more land is needed to support each person and the biocapacity of Earth goes up. (13.4) K/U
23. An ecological reserve exists when the biocapacity of a region exceeds its population's ecological footprint. (13.4) K/U
24. As a global community, we need to safeguard and enhance biodiversity through conservation and sustainable practices. (13.4) K/U
25. It is difficult to predict the future of the human population with any certainty, since the assumptions that are made when creating a projection may change. (13.4) K/U

Match each term on the left with the most appropriate description on the right.

26. (a) zero population growth
    (b) age structure
    (c) replacement rate
    (d) energy pyramid

    (i) rate at which people have children to live in their "place" when they die
    (ii) situation in which the death rate and the birth rate are in equilibrium
    (iii) distribution of ages among males and females of a population
    (iv) tool used by researchers to track the usable energy in a food chain (13.1, 13.2, 13.4) K/U

27. (a) salinization
    (b) aquaculture
    (c) sustainable agriculture
    (d) greenhouse gases
    (e) renewable resources
    (f) global hectare

    (i) practice of growing food using less energy than industrialized agriculture
    (ii) naturally occurring chemicals and substances that can be replenished by natural processes
    (iii) buildup of salt products due to the overuse of resources
    (iv) practice of raising fish and shellfish for crops
    (v) chemicals in the atmosphere that absorb and/or reflect thermal energy
    (vi) one hectare with an average capacity for production and waste absorption (13.2, 13.4) K/U

Write a short answer to each question.

28. Why does the replacement rate need to be just higher than two children per couple to achieve zero population growth? (13.1) K/U
29. With the domestication of plants and animals, human populations were transformed from small mobile groups of hunter-gatherers into societies in more permanent villages and towns. How did this affect food production? (13.1) K/U

30. Use **Figure 1** to answer the following questions. (13.1) K/U

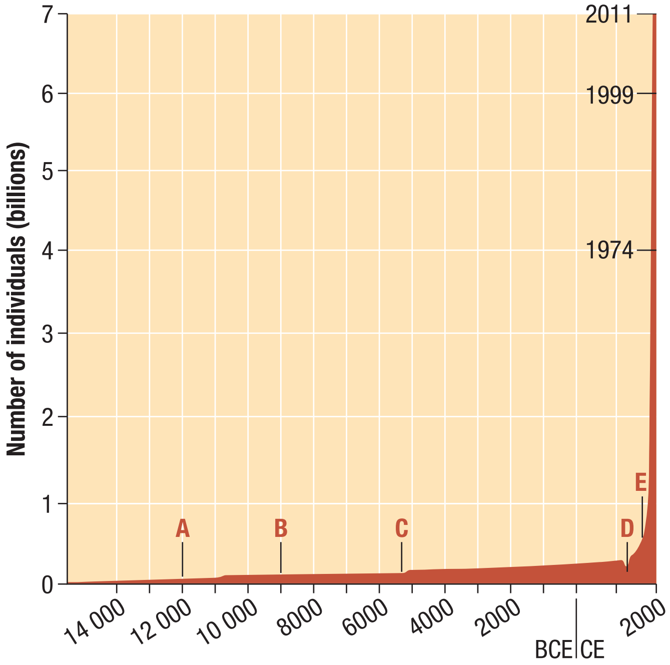


Figure 1

(a) Which label (A to E) on the graph represents the transformation of human populations from groups of hunter-gatherers into agriculturally based societies?

(b) Which label on the graph represents the beginning of the industrial and scientific revolutions?

(c) Which label on the graph represents the impact of the bubonic plague on population growth?

(d) Approximately how many years ago did the population begin to grow exponentially?

31. Science and technology have been influential throughout much of human history in terms of their social and environmental impacts. Explain the social impact of antibiotics. (13.1) K/U

32. Who may identify themselves as Aboriginal peoples in Canada? (13.1) K/U

33. What characteristics of a country's population are prevalent in the transition stage of the demographic transition model? (13.1) K/U

34. How has the industrialization of agriculture affected people who live in rural areas? (13.2) K/U

35. According to the United Nations, what is the minimum critical diet or minimum amount of energy that should be consumed each day? (13.2) K/U

36. List five processes that contribute to the loss of soil fertility. (13.2) K/U

37. Under what condition are fish considered to be a renewable resource? (13.2) K/U

38. What does the term "aquaculture" refer to? (13.2) K/U

39. (a) What are the United Nations Millennium Development Goals?

(b) What needs to happen for these goals to be achieved? (13.4) K/U

40. What are the drylands? How much of Earth's land surface do they cover? (13.4) K/U

41. Copy and complete this sentence: It is estimated that about ____ % of the world's known species will be at an increasingly higher risk of extinction for every ____ °C rise in global temperature. (13.4) K/U

42. What is vertical farming? (13.4) K/U

Understanding

43. (a) List four ways that humans have avoided the effects of density-dependent regulating factors, such as the availability of food, water, and shelter.

(b) How have each of these ways reduced the regulating factor? (13.1) K/U

44. How has the domestication of plants and animals affected the carrying capacity of Earth? Explain. (13.1) K/U

45. What are the stages of the demographic transition model? (13.1) K/U

46. What stage of the demographic transition model is Canada currently in? Describe this stage. (13.1) K/U

47. What are some of the challenges associated with living in concentrated groups in towns and cities? (13.2) K/U

48. According to the World Food Programme, what are the five key causes of hunger? (13.2) K/U

49. Why is industrialized farming considered to be high-input farming? (13.2) K/U

50. How does sustainable agriculture help to increase biodiversity? (13.2) K/U

51. What are the principal greenhouse gases that enter the atmosphere because of human activities? (13.2) K/U

52. How do low-impact diets reduce our global footprint? (13.2) K/U

53. What happens when our demand for resources is greater than our level of biocapacity? (13.4) K/U

54. What does it mean when we say that a species is threatened? (13.4) K/U

55. What does the ecological footprint measure? (13.4, 13.5) K/U

56. What is a green building? (13.4) K/U

Analysis and Application

57. (a) Use a table to summarize the advantages and disadvantages of aquaculture.
    (b) Do the advantages of aquaculture outweigh its disadvantages? Explain your answer. (13.2) K/U T/I C

58. (a) What are some density-dependent factors that affect humans at higher population densities?
    (b) How have these factors been addressed in industrial societies? (13.1) K/U T/I

59. It has been suggested that rangelands could be used to raise wild grazing animals for meat, instead of using farmland to raise conventional livestock.
    (a) What are some possible benefits of this idea?
    (b) What are some of the drawbacks? (13.2) K/U A

60. Use **Figure 2** (below) to answer the following questions. (13.1) K/U A
    (a) Which label (D, E, or F) represents each of the following?
        (i) reproductive stage
        (ii) pre-reproductive stage
        (iii) post-reproductive stage
    (b) Which country (A, B, or C) appears to have the fastest rate of population growth? Explain your answer.
    (c) Which country (A, B, or C) appears to have the slowest rate of population growth? Why?
    (d) From your analysis of the graphs, what statement could you make about life expectancy in each country?

61. **Table 1** contains Human Development Index 2010 data from the United Nations Development Programme. It shows the per capita carbon dioxide emissions for 1990 and 2006. (13.2, 13.4) K/U A

Table 1

Country	Carbon dioxide emissions per capita 1990 (tonnes)	Carbon dioxide emissions per capita 2006 (tonnes)
Canada	16.2	16.7
People's Republic of China	2.1	4.6
United States	19.0	19.0

    (a) When compared with the carbon dioxide emissions for Canada and the United States, the emissions for China appear small. Why should we be concerned about the increase in carbon dioxide emissions for China over this period of time?
    (b) What other factors might need to be considered to understand the "bigger picture" of these emissions?

62. Suggest ways that high school students like you could promote more sustainable agriculture. (13.2) K/U A

63. Should governments eliminate all fishing subsidies? By what other means could governments support their fishing industries? (13.2) T/I A

64. Suggest ways that we can use Earth's fresh water more sustainably. (13.2) K/U A

65. Freshwater supplies can be increased by building dams to store water for later use. Use a table to present some advantages and disadvantages of using dams or reservoirs to store and supply fresh water. (13.2) K/U C

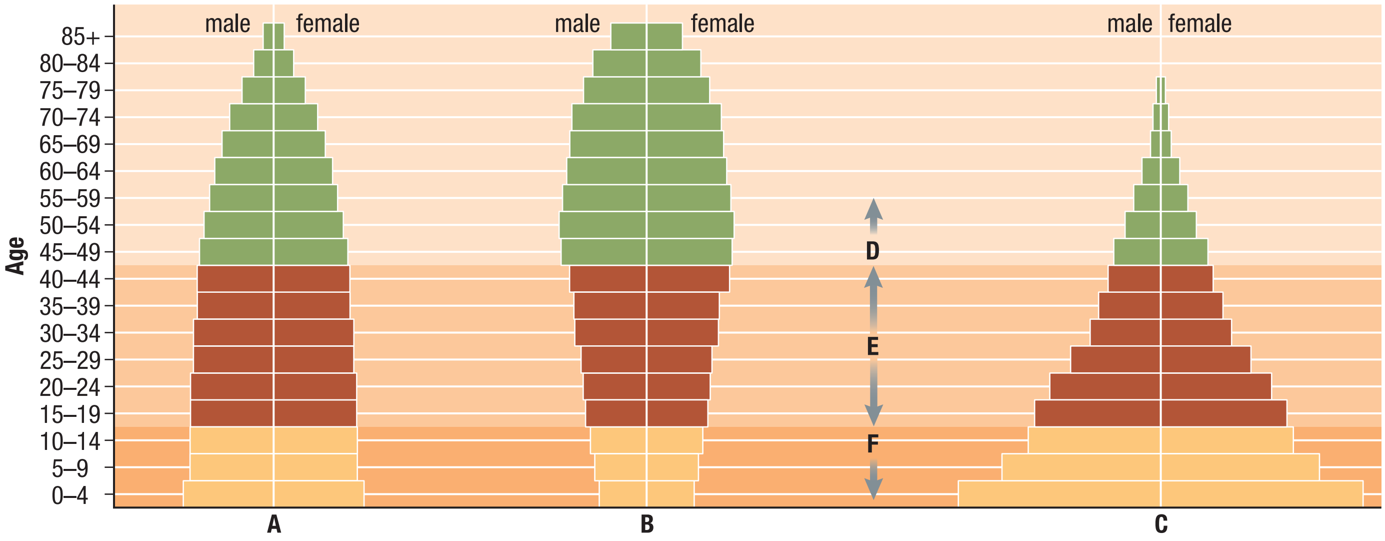


Figure 2

66. The data in **Table 2** come from the Human Development Index (HDI) 2010 report, issued by the United Nations Development Programme. The HDI is a comparative measure of well-being: life expectancy, literacy, education, and standard of living for countries worldwide. It is used to determine whether a country is developed, developing, or underdeveloped. It is also used to measure the impact of economic policies on the quality of life. Based on these data from the HDI, Canada and the United States are considered to be very high human-development countries, Argentina and Mexico are high human-development countries, China and Suriname are medium human-development countries, and Yemen and Nigeria are low human-development countries. (13.1, 13.2, 13.3, 13.4, 13.5) K/U C A

Table 2

Country	Gross national income (GNI) ($ per capita)	Life expectancy at birth (years)	Mean years of schooling (years)	CO$_2$ emissions per capita (tonnes)
Canada	38 668	81	16	17.3
United States	47 093	79	15.7	19.5
Argentina	14 603	76	15.5	4.1
Mexico	13 791	77	13.4	4.1
China	7 258	74	11.4	4.3
Suriname	7 092	69	12.0	5.3
Yemen	2 386	64	8.6	not available
Nigeria	2 156	48	8.9	0.8

(a) What correlations can you see in the data in Table 2? Remember that correlations do not necessarily imply causality.

(b) Do you think you would see an increase in life expectancy in any of these countries if their gross national incomes (GNIs) increased?

(c) If Canada and the United States were forced to reduce their carbon dioxide emissions by 50 % overnight, what might happen to their GNIs immediately and over time?

(d) Is it possible for China, as a developing country, to increase its GNI without increasing its carbon dioxide emissions? Explain.

(e) How might climate or geography affect a country's carbon dioxide emissions?

(f) Create a different question about the data in Table 2. Have your classmates answer your question.

67. The following descriptions represent population or environmental dilemmas—situations that require action because they have an impact on our planet. Rate each description according to the following scale:

1 = strongly agree
2 = agree
3 = neutral (neither agree nor disagree)
4 = disagree
5 = strongly disagree

Give reasons for your rating. (13.1, 13.2, 13.3, 13.4, 13.5) K/U A

(a) With a world population of almost 7 billion, we need to drill for more oil to fuel all the cars that people drive.

(b) To feed all the people on our planet, people in developed countries should reduce their consumption of meat.

(c) With a world population as large as ours, pollution is a fact of life and we should not waste money trying to prevent it.

(d) We do not need to worry about the future as much as some people say we should. Developments in science and technology will ensure that we have adequate supplies of food and energy.

(e) To provide enough food for all the people on our planet, we need to use pesticides and chemical fertilizers, and we need to create genetically modified foods.

(f) With our growing population, jobs are more important than the environment.

(g) I am only one person on this planet. What I do does not make a difference.

(h) All cars that are manufactured should be as fuel efficient as possible, regardless of the cost.

(i) As our population continues to grow, we need to use as much land as possible for living and for growing food, even if this means cutting down old growth or tropical forests.

(j) The key to solving the global challenges we are now facing is to reduce rapid population growth.

Evaluation

68. Why is waste considered to be one of the most important environmental issues? (13.2, 13.4, 13.5) K/U T/I

69. Persistent organic pollutants (POPs) are toxic substances, such as dioxins, DDT, and hexachlorobenzene, that are formed from organic compounds. They are made in industrial processes such as bleaching paper products, they are found in pesticides and herbicides, and they are produced during the combustion of wastes. Why are POPs considered problematic if they are organic? What problems could they cause in the environment? (13.2, 13.4) T/I

70. The main goal of agriculture is to provide an adequate supply of good-quality and affordable food. Has this goal been achieved at a global level? Explain your reasoning. (13.4) K/U T/I

71. Emergency shipments of food are often sent to countries that are experiencing famines. However, the food is not always used. Suggest possible reasons for this. (13.4) T/I

72. Identify the global environmental issue that you think is the most important in terms of the future of the human population. (Some possible issues are population growth, pollution, global warming, and agricultural issues.) Explain why you think the issue you identified is the most important. In your explanation, include a description of the issue, the extent of the problem, and possible solutions. (13.1, 13.2, 13.4) K/U T/I A

73. Is pollution always caused by human activities? Explain your answer. (13.2) K/U T/I

74. Humans have two options for limiting population growth: we can make a global effort to limit our own population, or we can wait until the environment does it for us.
   (a) Briefly address each option.
   (b) What methods could be used to achieve a global decline in birth rate?
   (c) What environmental events could occur if we do not limit our population? (13.1, 13.2) K/U A

75. Suggest economic and ecological advantages and limitations for each of the following situations. (13.2, 13.4) K/U A
   (a) using more land for growing crops by clearing tropical forests and irrigating arid lands
   (b) catching more fish in the oceans
   (c) producing more fish and shellfish using aquaculture
   (d) increasing the yield of crops per hectare of cropland
   (e) using fertilizers and pesticides

76. Water conservation is necessary and important. How do the 3 R's (reduce, reuse, and recycle) apply to water conservation? (13.2, 13.4) K/U T/I A

Reflect on Your Learning

77. Some artists express their concerns about pollution in songs, poetry, and visual and digital arts. How would you artistically express how you feel about pollution? T/I C A

78. While many resources are renewable, some are not. Fossil fuels are not renewable. How do you feel about the ways that fossil fuels are extracted and used? Do you worry about pollution, resource consumption, or land conversion and degradation? What is the one concern that you would like to be addressed? T/I A

79. What are the three most important actions you would take to reduce hunger in each area? T/I A
   (a) your local community
   (b) Canada
   (c) the world

80. A fast-food restaurant in Sweden has begun to post the carbon dioxide emissions associated with producing each of its burgers. The environmental section of the restaurant's website says, "We are part of the problem and therefore want to be part of the solution." Would you like to see this information posted in restaurants in Canada? Why or why not? Do you think it would change the way you eat? Explain why or why not.

Research

WEB LINK

81. What is the biggest public-health problem in the world today? Conduct online research to investigate what we are doing to solve this problem. Write a newspaper-style article detailing your findings. K/U T/I C

82. Different species of fish are harvested using different methods, and some methods are more sustainable than others. Use the Internet to learn which species are harvested most sustainably. Explain how these sustainable methods work. T/I

83. Using the Internet and other sources, find out more about the Great Pacific Garbage Patch. Use your findings to answer the following questions. T/I A
   (a) When and how was the Great Pacific Garbage Patch discovered?
   (b) How was it formed?
   (c) What are the sources of the pollutants?
   (d) What is the photodegradation of plastic, and how does this further affect the ocean?
   (e) What effects does the floating garbage have on wildlife?
   (f) Is this the only oceanic garbage patch? If there are others, where are they located?

84. Many alternative agricultural techniques are reducing soil erosion. Use the Internet and other sources to research one of the following techniques:
   - conservation tillage systems
   - windbreaks
   - terracing

   Create a poster to explain the environmental benefits of this technique. T/I C

85. Use the Internet or other sources to find out what people in other countries are doing to make their lifestyles more sustainable. Create a poster or brochure to outline ways that people in Canada could make better use of our natural resources. K/U T/I C A

One Planet, One Future: Population Growth in a Finite Environment

Globally, the human population uses the equivalent of 1.5 Earths to support our consumption of natural resources and absorb our wastes. If we continue in this manner, we may need the equivalent of two Earths to support us by 2030. We cannot continue to turn resources into waste faster than waste can be turned back into resources. This is referred to as ecological overshoot, and it depletes Earth's limited resources. It results in overfishing, deforestation, increased carbon dioxide emissions, and less fresh water (**Figure 1**).

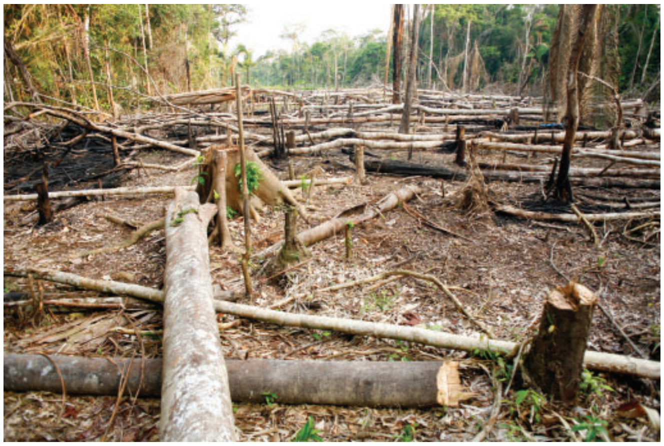


Figure 1 Slash and burn farming in Peru reduces forest cover and destroys habitat.

Humans interact with countless other species—we are just one in over 2 million identified species on the planet. However, our present actions are resulting in an ongoing loss of biodiversity (**Figure 2**). According to the United Nations Development Programme, our activities are causing extinctions to occur at up to 1000 times their natural rate.

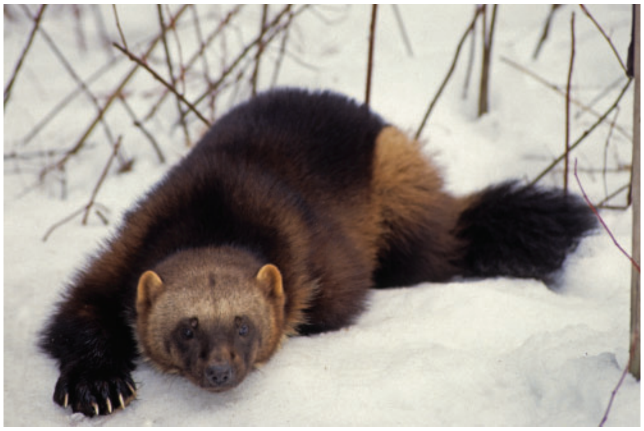


Figure 2 The last confirmed sighting of a Vancouver Island wolverine was in 1992. It is now believed to be extinct.

Our growing global population is creating an ever-increasing demand on nature. We need to alter our lifestyle to reduce our consumption of resources. All forms of life, including humans, depend on resources. We need to re-think the way we live, get around, manufacture goods, produce food, and provide services so that we can live within our planetary means and be sustainable as we approach the middle of the twenty-first century.

The Issue

Consider one problem created by the interaction between the growing human population and the abiotic or biotic environment. Some possible issues are listed below:

- non-sustainable agricultural techniques, which result in deforestation and/or habitat loss
- overfishing, which results in depleted fish stocks
- overgrazing of cattle, which results in desertification
- industrial CO_2 emissions, which result in increased levels of greenhouse gases
- municipal wastes, which result in water pollution
- potential biotic factors and colony collapse disorder, which result in crop or food supply shortages
- another issue that interests you, with your teacher's approval

After choosing an environmental issue, consider the following questions:

- What environmental problems are being caused by this issue?
- What are the implications for this issue in the future, as the human population continues to grow?
- What decisions need to be made now?
- What actions need to be put in place to ensure a sustainable future for the human population?

Goal

To choose an environmental issue related to the growing human population and examine its current status and future outlook

Research

After choosing and defining an environmental issue, conduct research to gain an understanding of its current status and future outlook. As you conduct your research, consider the decisions that need to be made and the actions that need to be put in place to ensure a sustainable future for the human population.

Consider the following questions:

- What is the current status of the environmental problem?
- What are the concerns, and how serious are these concerns?
- Who is responsible for the status of the issue? Is it mostly a local, regional, or global issue?
- Is the current situation sustainable?
- What effects does the issue have on the survival of other species?
- What are the trends in the issue?
- How will the increasing human population affect the issue?
- What are the implications for biodiversity?

Possible Solutions

Based on your research and your understanding of the environmental issue, answer the following questions:

- What needs to be done to solve future problems?
- Are new technologies available to reduce the impacts of the problem?
- What actions can individuals take locally to help?
- What national or international actions need to be taken?
- How will these actions benefit other species and protect biodiversity?

Communicate

Present your findings in an audiovisual format or a written report. Choose a format that is suitable for your intended audience. For example, play is often an effective tool to help young people examine issues and concerns, and understand how they can alter their lifestyle to encourage sustainability. You could communicate your findings to younger students through a video game or board game. You could communicate your findings to a more adult audience through a documentary.

Whichever format you choose, be sure to support your findings and suggestions with clearly presented data.

WEB LINK

ASSESSMENT **CHECKLIST**

Your completed Unit Task will be assessed according to the following criteria:

Knowledge/Understanding

✓ Demonstrate understanding of how humans interact with the natural world and how the growth of the human population has changed this interaction over time.

✓ Recognize ways that humans exploit the natural world, in terms of our ecological footprint.

✓ Demonstrate knowledge of how humans must change so that we can live more sustainably.

Thinking/Investigation

✓ Research applications of new technologies to help lessen the human impact on the natural world.

✓ Research ways that you can make a difference in your personal ecological footprint.

Communication

✓ Explain how the growth of the human population affects biodiversity.

✓ Explain how population models help demographers chart the course of the human population.

Application

✓ Apply your knowledge of ecological footprints to your everyday life—in the classroom and beyond.

UNIT 5 SELF-QUIZ

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

For each question, select the best answer from the four alternatives.

1. Which term refers to the number of organisms of the same species distributed within the usable area of a habitat? (12.1) K/U
   (a) population size
   (b) ecological density
   (c) population density
   (d) per capita growth
2. Which type of distribution is common for populations in which individuals repel each other because resources are in short supply? (12.1) K/U
   (a) unpredictable
   (b) uniform
   (c) clumped
   (d) random
3. Which of the following summarizes the demographic characteristics of a population? (12.2) K/U
   (a) survivorship curve
   (b) age-specific survivorship
   (c) age-specific mortality
   (d) life table
4. Which statement best describes a type III survivorship curve? (12.2) K/U
   (a) Most individuals die during their reproductive years.
   (b) Individuals die at a constant rate throughout time.
   (c) Most individuals die of old age.
   (d) Most individuals die early in life.
5. Which type of growth is exhibited by a population that grows continually at a fixed rate in a fixed time interval? (12.3) K/U
   (a) linear growth
   (b) geometric growth
   (c) exponential growth
   (d) logistic growth
6. Which type of curve is a smooth curve that shows the long-term logistical growth of a population? (12.3) K/U
   (a) straight line
   (b) J-shaped curve
   (c) S-shaped curve
   (d) negatively sloped
7. Which factor is a density-independent regulator of population size? (12.4) K/U
   (a) disease
   (b) competition for food
   (c) parasitism
   (d) drought
8. As the number of raccoons in a forest increases, the availability of nesting sites limits population growth. What does this situation illustrate? (12.4) K/U
   (a) density-dependent factor
   (b) intraspecific capacity
   (c) intraspecific competition
   (d) density-competition factor
9. Polar bears kill and eat seals for survival. What does this situation illustrate? (12.5) K/U
   (a) predation
   (b) parasitism
   (c) resource partitioning
   (d) intraspecific competition
10. Which term could be used for the relationship between flowering plants and animal pollinators? (12.5) K/U
    (a) mutualism
    (b) commensalism
    (c) parasitism
    (d) mimicry
11. What was the probable origin of the HIV (human immunodeficiency virus)? (13.1) K/U
    (a) cattle
    (b) monkeys
    (c) pigs and ducks
    (d) chimpanzees
12. Which of the following best describes the pre-industrial stage of the demographic transition model? (13.1) K/U
    (a) Food production rises, and healthcare and sanitation improve.
    (b) Birth and death rates are high, and population grows slowly.
    (c) People move to cities, and population growth slows.
    (d) Zero population growth is reached.
13. What percentage of the world's food do ocean fisheries supply? (13.2) K/U
    (a) 77 %
    (b) 16 %
    (c) 22 %
    (d) 7 %
14. Which statement best describes traditional agriculture? (13.2) K/U
    (a) It uses mostly human and animal labour.
    (b) It uses large amounts of fossil fuels.
    (c) It uses synthetic fertilizers or pesticides.
    (d) none of the above

15. What is a trophic level? (13.2) K/U
    (a) model that depicts the flow of energy
    (b) energy-transfer level in a food web
    (c) study of energy transformations
    (d) pictorial representation of the feeding relationships among organisms
16. Which of the following best describes erosion? (13.2) K/U
    (a) addition of salt products due to the overuse of resources
    (b) decrease in the productive potential of arid or semi-arid land by 10 % or more
    (c) movement of soil components from one place to another
    (d) layer of soil that usually contains limited organic matter
17. Why has Earth's carrying capacity increased? (13.2) K/U
    (a) Humans can live in closer proximity to each other than other organisms can.
    (b) Human agricultural practices have displaced other organisms, giving the human population more space.
    (c) Technological advancements have modified the environment.
    (d) The human population has reduced its agricultural needs, increasing the amount of space available.
18. Which resource is non-renewable? (13.4) K/U
    (a) natural gas
    (b) water
    (c) sunshine
    (d) wood
19. According to *The Living Planet Report*, by what percentage have vertebrate populations declined over the last 40 years? (13.4) K/U
    (a) 30 %
    (b) 40 %
    (c) 50 %
    (d) 60 %
20. Which of the following does not affect an individual's ecological footprint? (13.4) K/U
    (a) population size
    (b) amount of resources used
    (c) efficiency of resources use
    (d) amount of waste produced

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

21. The population measurement that looks at the distribution of organisms within the usable areas of a habitat is known as ecological density. (12.1) K/U
22. The dispersion pattern in which organisms are spread throughout a habitat in an unpredictable manner is known as clumped dispersion. (12.1) K/U
23. Population growth is determined by immigration and emigration. (12.2) K/U
24. At the beginning of a semester, a Grade 12 Biology class had a population of 27 students. During the semester, 4 students were added to the class and 1 student moved to another school. The population change was 3. (12.2) K/U
25. At the beginning of a semester, a Grade 12 Biology class had a population of 27 students. During the semester, 4 students were added to the class and 1 student moved to another school. The population growth rate was 3 %. (12.3) K/U
26. A population of 1000 yeast cells is growing in a culture test tube. If the growth rate is 25 yeast per hour, it will take 2 h for the population to reach 1500 yeast cells. (12.3) K/U
27. Any resource that is in the shortest supply is known as a density-independent factor. (12.4) K/U
28. Density-independent factors limit the growth of a population, regardless of the population density. (12.4) K/U
29. A protist lives in the gut of a termite, digesting cellulose that the termite cannot digest. This allows the termite to use the nutrients from the cellulose. If the protist is removed, both the protist and the termite will die. This is an example of mutualism. (12.5) K/U
30. Prey species evolve defence mechanisms, such as parasitism, to protect themselves against predators. (12.5) K/U
31. The current human population is approximately 7 million people. (13.1) K/U
32. An epidemic is the worldwide spread of a disease. (13.1) K/U
33. Energy pyramids show the flow of energy from one producer to another producer. (13.2) K/U
34. Water is an essential resource that is being negatively affected by many types of pollution. (13.2) K/U
35. The effects of conservation by an ever-increasing population are overburdening Earth's natural resources. (13.4) K/U

UNIT 5 REVIEW

K/U Knowledge/Understanding T/I Thinking/Investigation C Communication A Application

Knowledge

For each question, select the best answer from the four alternatives.

1. In the grasslands of Canada, prairie dogs live in colonies that are isolated from other colonies by large, unoccupied areas of land. Which term best describes this situation? (12.1) K/U
   (a) crude density
   (b) ecological dispersion
   (c) uniform dispersion
   (d) clumped dispersion
2. An orchard contains 20 apple trees in an area of 2.0 ha. What is the crude density of the tree population? (12.1) K/U
   (a) 40 trees/ha
   (b) 0.10 ha/tree
   (c) 10 trees/ha
   (d) 4.0 trees/ha
3. Which of the following best describes fecundity? (12.2) K/U
   (a) average time between the birth of an offspring and the birth of its offspring
   (b) relative proportion of males and females in the population
   (c) potential for a species to produce offspring during a lifetime
   (d) level of parental care given to offspring
4. A population grows rapidly during breeding season and then declines through the year, until the next breeding season. Which type of growth does this population exhibit? (12.3) K/U
   (a) linear growth
   (b) geometric growth
   (c) exponential growth
   (d) logistic growth
5. Which expression can be used to estimate the time it takes for a population to double? (12.3) K/U
   (a) $\frac{[(n + l) - (m + E) \times 100]}{n}$
   (b) $\frac{0.69}{r}$
   (c) $\frac{N(t + l)}{N(t)}$
   (d) $\frac{[(m + I) - (n + E) \times 200]}{C}$
6. Overpopulating rabbits in Australia were finally controlled by a disease that spread through their populations. The mortality rate in regions with a large population was higher than the mortality rate in regions with a small population. What does this situation illustrate? (12.4) K/U
   (a) density-dependent effect
   (b) density-independent effect
   (c) interspecific competition
   (d) intraspecific competition
7. Under ideal conditions, a population of bacteria can grow to more than 10^{36} bacteria in a 24 h period. Which property of the population does this situation illustrate? (12.4) K/U
   (a) density
   (b) carrying capacity
   (c) biotic potential
   (d) growth rate
8. Humans compete with many other species for food. However, the most important competition in many areas is competition between humans for food. What does this situation illustrate? (12.4) K/U
   (a) density dependence
   (b) interspecific competition
   (c) intraspecific competition
   (d) density independence
9. A panda bear consumes a diet that consists primarily of eucalyptus leaves. What would the panda bear be considered? (12.5) K/U
   (a) specialist and herbivore
   (b) generalist and herbivore
   (c) specialist and carnivore
   (d) generalist and carnivore
10. The Monarch butterfly and Viceroy butterfly have an undesirable taste and look very similar. What does this situation illustrate? (12.5) K/U
    (a) camouflage
    (b) behavioural adaptations
    (c) Batesian mimicry
    (d) Mullerian mimicry
11. What were the first animals to be raised by humans? (13.1) K/U
    (a) sheep, goats, and pigs
    (b) horses
    (c) pigs, silkworms, and water buffalos
    (d) turkeys

12. When did the major changes in agriculture, manufacturing, mining, transportation, and technology happen? (13.1) K/U
    (a) during the Green Revolution
    (b) during the Agricultural Revolution
    (c) during the Industrial Revolution
    (d) during the Peasant's Revolt
13. A human population is living without medical care in a developing country. What would its age-structure diagram most likely resemble? (13.1) K/U
    (a) rectangular pyramid
    (b) triangular pyramid
    (c) oval pyramid
    (d) no pyramid
14. Which of the following best illustrates exploitation of the environment? (13.2) K/U
    (a) poor farming practices
    (b) floods and tropical storms
    (c) not enough money to buy food
    (d) refugees uprooted from arable land
15. Which statement about traditional agriculture is correct? (13.2) K/U
    (a) About 10 units of non-renewable fossil fuel energy are needed to produce 1 unit of food.
    (b) About 10 units of renewable fossil fuel energy are needed to produce 1 unit of food.
    (c) About 1 unit of energy from human labour is needed to produce 10 units of food.
    (d) About 1 unit of energy from human labour is needed to produce 1 unit of food.
16. What can be considered to be the main cause(s) of soil erosion? (13.2) K/U
    (a) human activities
    (b) human activities and wind
    (c) human activities, wind, and forest fires
    (d) human activities, wind, and water
17. What is atmospheric deposition? (13.2) K/U
    (a) pollution of the air by atmospheric pollutants
    (b) pollution of the land and water by atmospheric pollutants
    (c) pollution of the land by atmospheric pollutants
    (d) pollution of the water by atmospheric pollutants
18. According to ecological footprint data, how does Ontario's biocapacity per person compare with the global biocapacity per person? (13.4) K/U
    (a) 4 times as large
    (b) one-fourth the size
    (c) 10 times as large
    (d) one-tenth the size
19. Which of the following would have the greatest biocapacity? (13.4) K/U
    (a) desert
    (b) mountain range
    (c) tropical rainforest
    (d) glacier
20. Which of the following best describes an ecological reserve? (13.4) K/U
    (a) situation in which resources are turned into waste products faster than waste products can be turned back into resources
    (b) situation in which the biocapacity of an area exceeds the footprint of the area
    (c) decrease in mortality rate and increase in birth rate
    (d) amount of carbon dioxide emitted by the consumption of a particular person or group

Indicate whether each statement is true or false. If you think the statement is false, rewrite it to make it true.

21. The population density measurement that examines the distribution of organisms within usable areas of a habitat is known as biological density. (12.1) K/U
22. The mark-recapture method is a common sampling technique for species that continually move around, seeking protection, food, and shelter in areas that are hard to see. (12.1) K/U
23. Tracking animals provides useful information about their behaviour. (12.1) K/U
24. While measuring or estimating population size is necessary when studying populations, every effort should be made to be sure that the use of animals for research is valid, humane, and justifiable. (12.1) K/U
25. An open population is a population in which the factors that influence the number of organisms are open to natality and mortality only. (12.2) K/U
26. A cohort is a group of individuals of the same age. (12.2) K/U
27. The logistic growth model describes growth without limitation. (12.3) K/U
28. A sinusoidal curve is characteristic of logistic population growth. (12.3) K/U
29. Parasitism is a density-independent factor of population regulation. (12.4, 12.5) K/U
30. Barnacles are small crustaceans that are often found attached to whales. The barnacles are filter feeders, and they do not appear to harm the whales in any way. This relationship can best be described as commensalism. (12.5) K/U
31. Domestication of animals started at the same time in different parts of the world. (13.1) K/U

32. Human population growth changes over time and varies significantly by region. (13.1) K/U

33. Population pyramids represent gender distributions across a population. (13.1) K/U

34. Demographics for the Aboriginal populations of Canada suggest a population increase in the next decade due to large populations of young people. (13.1) K/U

35. The movement from urban areas to rural areas had advantages for human populations, but required the development of more services and infrastructure. (13.2) K/U

36. Water quality is threatened in many areas, leading to erosion and nutrient loss. (13.2) K/U

37. High-input agriculture uses resources such as water and electricity to produce food. (13.2) K/U

38. Responding to the needs of a rapidly growing population can challenge a country's ability to manage its natural resources sustainably. (13.4) K/U

39. According to the Global Footprint Network, we use the equivalent of 1.5 planets to provide the resources we use and to absorb our waste. (13.4) K/U

40. A changing climate will alter a country's biodiversity. (13.4) K/U

Match each term on the left with the most appropriate description on the right.

41. (a) population density
    (b) emigration
    (c) age-specific fecundity
    (d) exponential population growth
    (e) logistic model

    (i) population growth that is increasing steadily by a constant ratio
    (ii) average number of offspring produced by females during each age interval
    (iii) population growth that is slowing as the population reaches *K*
    (iv) number of individuals per unit area or volume
    (v) movement out of a population (12.2, 12.3) K/U

42. (a) $\frac{dN}{dt} = B - D$
    (b) $\frac{dN}{dt} = (b - d)N$
    (c) $\frac{dN}{dt} = r_{max}N$
    (d) $d = \frac{D}{N}$
    (e) $\frac{dN}{dT} = r_{\max} N \frac{(K - N)}{K}$

    (i) population growth under ideal conditions
    (ii) logistic model of population growth
    (iii) exponential model of population growth
    (iv) per capita death rate
    (v) change in population size (12.3) K/U

Write a short answer to each question.

43. A 3.0 ha field contains a 1.0 ha pond. A colony of 90 ground squirrels lives in the field. Determine the ecological density of the population. (12.1) T/I

44. A backyard that measures 3.0 m by 4.0 m contains 215 dandelions. Determine the population density of the dandelions. Show your work. (12.1) T/I

45. Explain why a population may show clumped dispersion. (12.1) K/U

46. If the age-specific mortality of a population is 0.629, what is the age-specific survivorship? (12.2) K/U T/I

47. A population of prairie dogs in a field is increasing in size. At the beginning of one year, the population was estimated to be 200. Over the year, there were 90 births and 80 deaths. (12.2, 12.3) K/U T/I
    (a) What is the growth rate?
    (b) What is the per capita growth rate?

48. The per capita growth rate of a population is determined to be 0.23 organisms per week. If the population exhibits exponential growth, how long will it take for the population to double in size? (12.3) K/U T/I

49. What shape is a smooth curve that shows the effect of carrying capacity on the growth of a population? (12.3) K/U

50. What term refers to the maximum number of organisms that can be sustained by available resources over a given period of time? (12.3) K/U

51. A population of black flies in northern Ontario has an intrinsic growth rate of 0.34 per day. How long will it take for the population to double? (12.3) K/U

52. In natural populations, why does exponential growth not continue indefinitely? (12.3, 12.4) K/U

53. Explain when and why resource partitioning occurs. (12.5) K/U

54. Identify the relationship that is exhibited in each situation. Explain your reasoning. (12.5) K/U
    (a) A remora is a small fish that attaches itself to a shark. It rides with the shark, eating scraps of food that the shark leaves behind. The remora does not harm or help the shark.
    (b) In Africa, small birds perch on the head of a rhinoceros, eating the parasitic mites that infest the rhino's ears. The birds are protected from predators because few predators will attack a rhino.

55. How did raising livestock create change for humans? (13.1) K/U

56. How did the domestication of animals contribute to the spread of pathogens? (13.1) K/U

57. What is a sustainable population? (13.2) K/U

58. Historically, what did cities need to provide in order to support large concentrations of human populations adequately? (13.2) K/U

59. What can happen if a person consistently does not consume the minimum critical diet? (13.2) K/U

60. How can we all conserve energy and lessen the ecological footprint of farming? (13.2) K/U

61. What parts of Canada rely heavily on irrigation? (13.2) K/U

62. (a) Copy and complete this sentence: Currently, organic farming makes up only about ______ % of the agriculture in Canada, but it is growing at a rate of ______ % per year.
    (b) Based on the percentages in (a), what percentage of agriculture will be organic farming in 2 years, 5 years, and 10 years? (13.2) K/U T/I

63. What does the biocapacity per person refer to? (13.4) K/U

64. If the human population continues to grow at the same rate it grew over the previous century, in approximately how many years will it double? (13.4) K/U

65. Define and give an example of a non-renewable resource. (13.4) K/U

Understanding

66. What two things must a biologist know to determine population density? (12.1) K/U

67. Biologists captured and marked 100 butterflies. They later captured 115 butterflies and found that 5 were marked. Estimate the population size of the butterflies. (12.1) K/U

68. What is the best way to investigate the effects of factors that influence populations? (12.1) K/U

69. On an isolated island, what are the two determinants of the size of a population? (12.2, 12.3) K/U

70. A hypothetical population has a per capita growth rate of 3.5 % per year. Determine the approximate time needed for the population to double in size. Show your work. (12.3) K/U

71. At the beginning of one summer, a small pond contained 38 koi (an ornamental variety of the common carp). Over the summer, 15 koi were eaten by neighbourhood cats. There was no reproduction, but 20 koi were added. (12.2, 12.3) K/U
    (a) Determine the population size at the end of the summer. Show your work.
    (b) Determine the per capita growth rate of the population over the summer. Show your work.

72. A population of 100 animals is experiencing logistic growth. If $r_{\max} = 0.4$ and $K = 102$, calculate the value of r using the following equation: (12.3) K/U

$$r = r_{\max}\frac{(K - N)}{K}$$

73. At what point in the logistic growth model does the population grow quickly? Why? (12.3) K/U

74. Maple seeds that have sprouted on a forest floor must have nutrients, water, and space to grow. If they have sprouted in the shade of a much larger tree, they will not have enough sunlight to grow. Ecologically, what is this lack of sunlight called? (12.4) K/U

75. (a) What is coevolution?
    (b) Is coevolution usually restricted to two species? Explain. (12.5) K/U

76. Compare a fundamental niche with a realized niche. (12.5) K/U

77. Which type of population interaction is advantageous for one species but has no effect on the other species? (12.5) K/U

78. How would a Canadian Aboriginal population pyramid differ from a Canadian non-Aboriginal population pyramid? (13.1) K/U

79. How did the acquisition and use of language encourage human population growth? (13.1) K/U

80. Other than the development of vaccines and antibiotics, what factors help to improve public health? (13.1) K/U

81. How can the carrying capacity of Earth be increased or decreased? (13.2) K/U

82. Historically, what three general sources have supplied food for human populations? (13.2) K/U

83. Compare and contrast traditional agriculture with industrialized agriculture. (13.2) K/U

84. Why is water considered to be one of our most poorly managed resources? (13.2) K/U

85. What are some of the major causes of water pollution? (13.2) K/U

86. Why is Earth's biodiversity an important global issue? Explain, using examples. (13.4) K/U

87. List three ways that we can effect change in our approach to conservation. (13.4) K/U

88. What happens when the human demand for resources exceeds the ability of Earth's natural ecosystems to supply the resources? (13.4) K/U

89. Where and how does conservation begin? (13.4) K/U

Analysis and Application

90. Why would biologists use per capita population growth rates rather than total population growth rates? (12.1) K/U T/I

91. Use **Figure 1** to answer the following questions. (12.2) K/U T/I

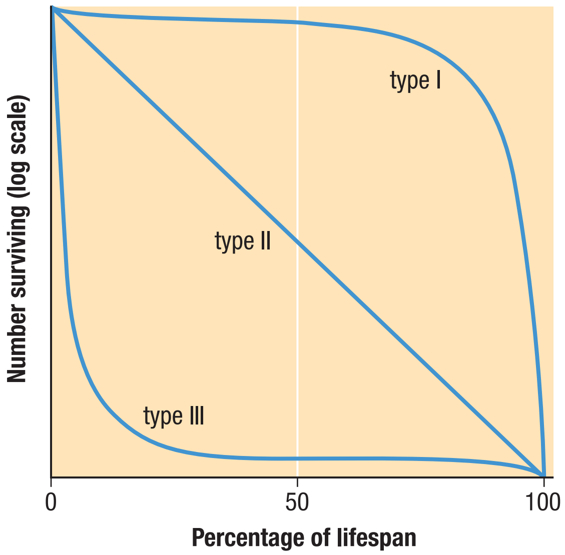


Figure 1

(a) Sea turtles are likely to die when they are young, but they have a good chance of surviving once they become larger. Which survivorship curve would best depict this? Explain.

(b) Which survivorship curve would best depict humans who are living in an environment with good medical care? Why?

(c) Which curve would best depict humans who lived early in the century, with the ravaging effects of polio and influenza outbreaks? Why?

92. In the logistic model of population growth, what is expected to happen to *r* when *N* > *K*? (12.3) K/U

93. Loons nest in pairs on a lakeshore but rarely share the small lake with another pair of loons. Is this density-dependent or density-independent population regulation? Explain your reasoning. (12.4) T/I

94. Why would an exotic species be able to establish itself so easily in Ontario? (12.5) T/I A

95. When populations of antelope and cheetahs coexist, what changes are likely to occur due to natural selection? (12.5) T/I

96. Epidemic diseases were not a serious problem for early hunter-gatherer societies. It was only when agriculture was developed that epidemics became a limiting factor for human populations. Why? (12.4, 13.1) K/U T/I

97. **Figure 2** is a graph that shows the number of lynx and hare pelts sold by trappers to the Hudson's Bay Company between 1845 and 1935. Use the graph to answer the following questions. (12.5) K/U T/I

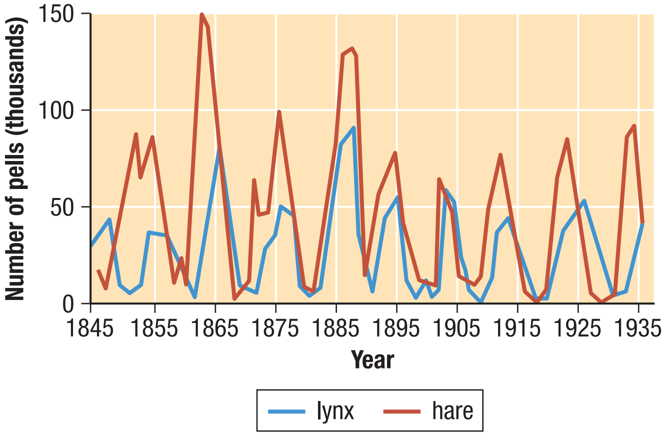


Figure 2

(a) Assuming that the number of pelts sold is a reflection of the populations of the two species, describe what happened to the populations of hares and lynx during the years shown.

(b) Describe how the changes in the two populations seem to be related to each other.

(c) Explain the relationship that would cause the changes shown in the graph.

98. Use **Figure 3** to answer the following questions. (13.1) K/U A

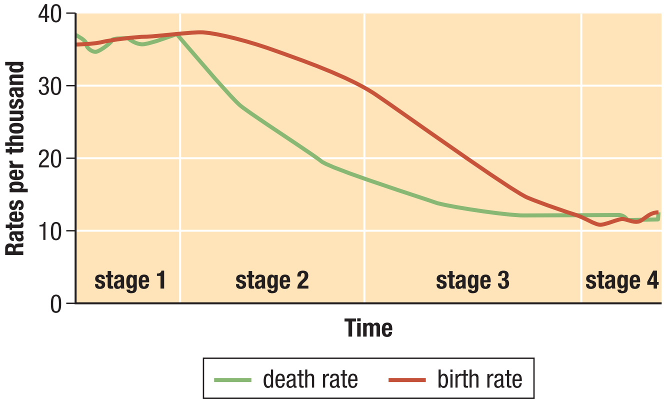


Figure 3

(a) Why is the death rate high and fluctuating in stage 1 of the demographic transition model?

(b) Why is the birth rate low in stage 4 (post-industrialization) of the demographic transition model?

(c) If there were a stage 5 in the demographic transition model, what do you think the characteristics of this stage would be? Name a country that could be in the hypothetical stage 5 today.

99. **Table 1** shows the world population in selected years since 1800. (13.1, 13.4) K/U T/I C

Table 1

Year	Population
1800	1 billion
1930	2 billion
1960	3 billion
1975	4 billion
1987	5 billion
1999	6 billion
2011	7 billion

(a) Create a line graph to represent the data in Table 1.
(b) Estimate the year in which the world population will reach 10 billion.
(c) If the world population continues to grow at the same rate, how old will you be when it reaches 12 billion?

100. Based on the differences in the three energy pyramids in **Figure 4**, a vegetarian would reason that being a vegetarian is good for the environment. Explain this line of reasoning. (13.2, 13.3, 13.4, 13.5) T/I

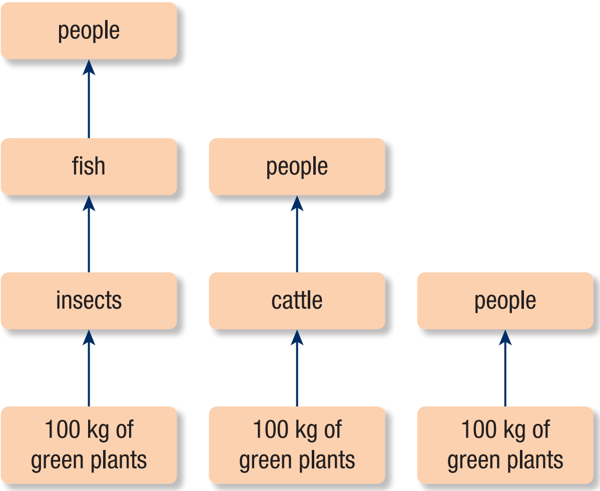


Figure 4

Evaluation

101. Why are a zebra's stripes an advantage that helps the zebra survive? (12.5) T/I

102. Since all land-dwelling animals require oxygen for respiration, is oxygen a limiting factor? (12.5) K/U T/I

103. Recent Census Canada data show that the population is growing in some areas of Canada, even though the birth rate has declined in these areas. Give three possible explanations for this. (12.2, 13.1) T/I

104. "What one person considers to be a pest, another person recognizes to be a desirable part of the web of life." Respond to this statement, explaining your position as if you were each of the following people (12.5, 13.1) K/U T/I C
(a) member of a First Nation
(b) cattle rancher

105. It has been suggested that the term "sustainable growth" is an oxymoron (a figure of speech in which incongruous or contradictory terms appear side by side). (13.1, 13.2, 13.3, 13.4, 13.5) K/U T/I A
(a) Based on the two words in this term, why do you think some theorists believe that sustainable growth is impossible?
(b) What might be a better term? Why?

106. How are the carrying capacity of Earth and the ecological footprint related? Explain your reasoning. (13.2, 13.3, 13.4, 13.5) K/U T/I

107. While urban centres have adverse effects on the environment and sometimes on the people who live in them, rural areas also have their issues. Is it healthier to live in the city or in the country? Defend your position with facts, not just opinions. (13.2, 13.3, 13.4) K/U T/I

108. There are many situations in which renewable resources are not renewable. Use an example to explain a situation in which renewable resources may not be renewable. (13.2, 13.3, 13.4) K/U T/I A

109. The term "human population growth" is subject to many misunderstandings and misconceptions. Summarize three misconceptions or misunderstandings, and suggest why they are incorrect. (13.1. 13.2, 13.4) K/U T/I

110. Do you think there is a relationship between carbon dioxide production and resource consumption? Explain your answer. (13.2, 13.4, 13.5) K/U T/I

Reflect on Your Learning

111. (a) What information in this unit did you know about before you began?
(b) What information in this unit was completely new to you?
(c) How has your knowledge about population dynamics changed, based on what you have read about in this unit? T/I

112. (a) Do you think that climate change is something we should be concerned about? Explain.
(b) Does climate change concern you enough to make lifestyle changes? Explain. T/I

113. (a) What kind of future would you like for yourself, your friends, your community or region, and your country? What kind of future do you see?
(b) Is the future you see the same as the future you want? What are your biggest concerns? T/I

114. (a) Why is sustainability important to you?
(b) What is changing in your community in an unsustainable way? What is changing in your community to become more sustainable? How do you feel about these changes?
(c) What would you change if you could? T/I

115. Respond to the following statement, based on what you have learned in this unit: "The colder winters we have experienced in parts of Canada over the last few years are evidence that all the concern about climate change is wrong." T/I

116. It has been said that children learn from what they are taught and what they observe. As adults, we are all teaching the children who observe us. T/I
(a) Do you think that you are a good environmental role model for the children of the world? Why or why not?
(b) Based on what you have learned in this unit, what changes would you make to become a better environmental role model?

117. Do you think that public awareness campaigns have made you more aware of the environmental, social, and economic dimensions of sustainability? How do you feel about the presentation of "worst-case scenarios" to encourage people to want more sustainability? How would you prefer to see these types of campaigns presented? T/I

118. A key component of cellphones is a lightweight metal called tantalum, which can hold an electric charge. It is found primarily in the rainforests of central Africa. Unfortunately, mining operations are destroying habitats and threatening wildlife. T/I
(a) How many cellphones have you already owned and discarded? Do you recycle your old cellphone when you get a new one? Are your new cellphones purchased out of necessity or want?
(b) How can we better educate the general public to reduce the number of new cellphones purchased in a lifetime?

119. (a) How big or small is your ecological footprint? How does it compare with the national average?
(b) Now that you have seen your impact on the planet, are there changes that you might consider so that you make less of an impact? How are you already trying to live sustainably?
(c) How might you encourage others to engage in more sustainable thinking or living? T/I

120. Some environmentalists believe that there are two levels of environmental quality:
- selective environmentalism, which involves the voluntary adoption of surface-level environmentally friendly options, such as recycling
- deep environmentalism, which involves prioritizing fundamental environmental issues so they become the foundation for all human activities

Do you think selective activities, such as recycling, are enough, or do we need to consider deeper environmentalism? T/I

121. Environmental stewardship refers to the responsible use and protection of the natural environment through conservation and sustainable practices. Have you considered student-level environmental stewardship? For example, you could hold a fish-friendly car wash by preventing soapy water, dirt, and phosphates from draining into sewers and ditches that lead straight to sources of fresh water. What other ways could you make some of your school events more environmentally friendly? T/I

Research

WEB LINK

122. Did the rats get a bad rap? Recent research in the garbage pits of London suggests that rats were not the vectors of the bubonic plague (**Figure 5**). Using the Internet and other sources, find out as much as you can about this research. What or who do scientists believe were the vectors of the disease, and why do scientists believe this? Create a poster for an advertising campaign to change the public perception of the maligned rats of the fourteenth century. K/U T/I C A

Lord, have mercy
on London.
I follow.
We fly.
Wee dye.
Keepeout.

Figure 5

123. As climate changes occur, they raise an important question: Can nature adapt to these changes? The answer may lie in the past. Throughout Earth's history, there have been periods when the climate changed dramatically. The result was the mass extinction of many species. A slow recovery followed. Some scientists believe that we are potentially facing the sixth great extinction. Using the Internet and other sources, find out more about the five previous mass extinctions on this planet and the possible sixth. How might the sixth extinction be different from the first five? Prepare a visual timeline, including the time period of each extinction and the organisms that were affected. T/I C A

124. The privatization of water and water services is a hotly contested topic worldwide. Water and water services are seen as a key government responsibility, and proposals for privatization often evoke strong opposition. Using the Internet and other sources, find out as much as you can about the privatization of water in Canada. Consider the following questions in your research:
   - Should water be treated as an economic good or service?
   - What attempts have been made to privatize water services in Canada and in other parts of the world?
   - How successful have the privatization attempts been?
   - How might water privatization affect countries with varying amounts of water resources?

   When you have finished your research, decide whether water privatization is positive or negative for communities. Present your position in a video, a poster, an audiovisual slide presentation, or another format of your choice. T/I C A

125. Can obese people suffer from malnutrition? The answer to this question may surprise you. Use the Internet and other sources to find out more about malnutrition. Consider the following questions:
   - What is the difference between chronic undernutrition and malnutrition?
   - What are the two most common nutritional deficiency diseases, and how do they differ?
   - Approximately how many people in the world are chronically undernourished or malnourished?

   Use your findings to answer the initial question in one or two paragraphs. T/I

126. Is a hybrid vehicle really the greener option? When comparing the environmental footprint of a hybrid vehicle with the environmental footprint of a non-hybrid vehicle, some theorists believe that we need to look at the total picture—the footprint from "dust to dust." The cost of the resources and the cost of disposal need to be compared with the benefits of the vehicle. Using the Internet and other sources, research the actual cost of a hybrid vehicle. Write a one-page report detailing the pros and cons of hybrid vehicles. Include answers to the following questions in your report:
   - What is the total cost of a hybrid vehicle? Is the sticker price all that should be considered when buying a hybrid?
   - What types of hybrids are available?
   - Is a hybrid SUV an oxymoron?
   - What would be the best choice of vehicle for you: a hybrid (if so, which type) or a non-hybrid? Explain your reasoning. T/I A

127. While vertical farms are still relatively rare around the world, the concept exists on a smaller scale in the form of green roofs. Green roofs are a step toward sustainable development. Use the Internet and other sources to find out more about the environmental benefits of green roofs. Use your findings to answer the following questions: T/I C A
   (a) What is a green roof? What is similar but not considered to be a green roof?
   (b) What are the environmental benefits of a green roof?
   (c) What are the financial benefits of a green roof?
   (d) Explain the basic construction techniques for the two types of green roofs that are now in use.
   (e) What is a brown roof?
   (f) Many countries, including Canada, use green-roof technology. Find and describe examples of green roofs in Canada and two other countries.
   (g) Are there disadvantages to a green roof? Explain.

APPENDIX A SKILLS HANDBOOK

A1 Safety

A1.1 Safety Conventions and Symbols

Although we make every effort to make the science experience a safe one, there are some inherent risks. These risks are generally associated with the materials and equipment used, and with disregard of safety instructions when conducting investigations. Most of these risks pose no more danger than we normally experience in everyday life. We can reduce these risks by being aware of the possible hazards, knowing the rules, behaving appropriately, and using common sense.

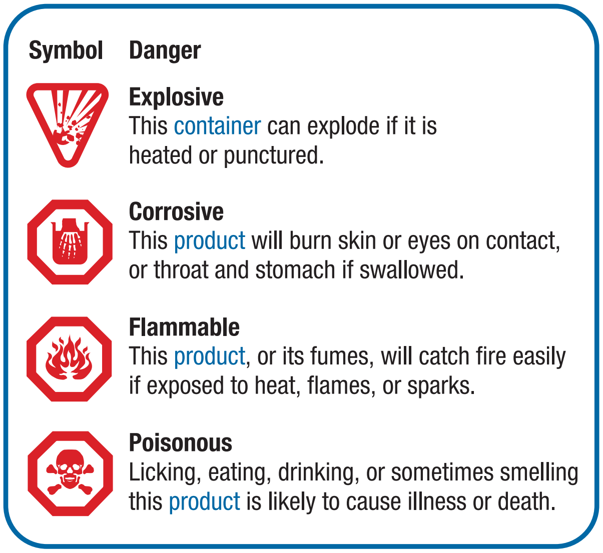
You share the responsibility not only for your own safety, but also for the safety of those around you (**Figure 1**). Always alert your teacher in case of an accident. In this textbook, chemicals, equipment, and procedures that are hazardous are indicated by the appropriate Workplace Hazardous Materials Information System (WHMIS) symbol or by ✋.

Figure 1 Taking the proper safety precautions will ensure a safe environment for you and your classmates.

WHMIS SYMBOLS AND HHPS

The Workplace Hazardous Materials Information System (WHMIS) provides workers and students with complete and accurate information about hazardous products. All chemical products supplied to schools, businesses, and industries must contain standardized labels and be accompanied by a Material Safety Data Sheet (MSDS). The MSDS provides detailed information about the product. Clear and standardized symbols are an important component of WHMIS (**Table 1**, next page). These symbols must be present on the product's original container and shown on other containers if the product is transferred.

The *Canadian Hazardous Products Act* requires manufacturers of consumer products containing chemicals to include a symbol that specifies the nature of the hazard and whether it is the container or the contents that are dangerous. In addition, the label must state any secondary hazards, first-aid treatment, and storage and disposal information. Hazardous Household Product Symbols (HHPS) are used to show the type of hazard. The shape of the frame around the symbol indicates whether the hazard is due to the contents or the container (**Figure 2**).



Symbol **Danger**

Explosive
This container can explode if it is heated or punctured.

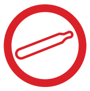
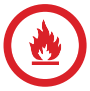
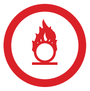
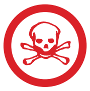
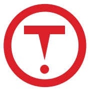
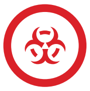
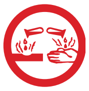
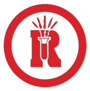
Corrosive
This product will burn skin or eyes on contact, or throat and stomach if swallowed.

Flammable
This product, or its fumes, will catch fire easily if exposed to heat, flames, or sparks.

Poisonous
Licking, eating, drinking, or sometimes smelling this product is likely to cause illness or death.

Figure 2 Hazardous Household Product Symbols (HHPS) appear on many products. A triangular frame indicates that the container is potentially dangerous. An octagonal frame indicates that the contents pose a hazard.

Table 1 The Workplace Hazardous Materials Information System (WHMIS)

Class and type of compounds	WHMIS symbol	Risks	Precautions
Class A: *Compressed Gas* Material that is normally gaseous and kept in a pressurized container		• could explode due to pressure • could explode if heated or dropped • possible hazard from both the force of explosion and the release of contents	• ensure container is always secured • store in designated areas • do not drop or allow to fall
Class B: *Flammable and Combustible Materials* Materials that will continue to burn after being exposed to a flame or other ignition source		• may ignite spontaneously • may release flammable products if allowed to degrade or when exposed to water	• store in designated areas • work in well-ventilated areas • avoid heating • avoid sparks and flames • ensure that electrical sources are safe
Class C: *Oxidizing Materials* Materials that can cause other materials to burn or support combustion		• can cause skin or eye burns • increase fire and explosion hazards • may cause combustibles to explode or react violently	• store away from combustibles • wear body, hand, face, and eye protection • store in container that will not rust or oxidize
Class D: *Toxic Materials Immediate and Severe* Poisons and potentially fatal materials that cause immediate and severe harm		• may be fatal if ingested or inhaled • may be absorbed through the skin • small volumes have a toxic effect	• avoid breathing dust or vapours • avoid contact with skin or eyes • wear protective clothing, and face and eye protection • work in well-ventilated areas and wear breathing protection
Class D: *Toxic Materials Long-Term Concealed* Materials that have a harmful effect after repeated exposures or over a long period		• may cause death or permanent injury • may cause birth defects or sterility • may cause cancer • may be sensitizers causing allergies	• wear appropriate personal protection • work in well-ventilated areas • store in appropriate designated areas • avoid direct contact • use hand, body, face, and eye protection • ensure respiratory and body protection is appropriate for the specific hazard
Class D: *Biohazardous Infectious Materials* Infectious agents or a biological toxin causing a serious disease or death		• may cause anaphylactic shock • includes viruses, yeasts, moulds, bacteria, and parasites that affect humans • includes fluids containing toxic products • includes cellular components	• special training is required to handle materials • work in designated biological areas with appropriate engineering controls • avoid forming aerosols • avoid breathing vapours • avoid contamination of people and/or area • store in special designated areas
Class E: *Corrosive Materials* Materials that react with metals and living tissue		• eye and skin irritation on exposure • severe burns/tissue damage on longer exposure • lung damage if inhaled • may cause blindness if contacts eyes • environmental damage from fumes	• wear body, hand, face, and eye protection • use breathing apparatus • ensure protective equipment is appropriate • work in a well-ventilated area • avoid all direct body contact • use appropriate storage containers and ensure non-venting closures
Class F: *Dangerously Reactive Materials* Materials that may have unexpected reactions		• may react with water • may be chemically unstable • may explode if exposed to shock or heat • may release toxic or flammable vapours • may vigorously polymerize • may burn unexpectedly	• handle with care, avoiding vibration, shocks, and sudden temperature changes • store in appropriate containers • ensure storage containers are sealed • store and work in designated areas

A1.2 Safety in the Laboratory

Safety in the laboratory is an attitude and a habit more than it is a set of rules. It is easier to prevent accidents than to deal with the consequences of an accident. Most of the following rules are common sense:

- Do not enter a laboratory unless a teacher or other supervisor is present, or you have permission to do so.
- Know your school's safety regulations.
- Tell your teacher about any allergies or medical problems you may have.
- Wear eye protection, a lab apron, and safety gloves when instructed by your teacher. Wear closed shoes.
- Tie back long hair and wear a protective lab coat over loose clothing. Remove any loose jewellery and finger rings.
- Keep yourself and your work area tidy and clean.
- Never eat, drink, or chew gum in the laboratory.
- Know the location of MSDS information, exits, and all safety equipment, such as the first-aid kit, fire blanket, fire extinguisher, and eyewash station, and be familiar with their contents and operation.
- Avoid moving suddenly or rapidly in the laboratory, especially near chemicals or sharp instruments.
- Never change anything, or start an activity or investigation on your own, without your teacher's approval. Before you start an investigation that you have designed yourself, get your teacher's approval.
- Never work in a crowded area or alone in the laboratory.
- Always wear approved eye protection in a laboratory. Keep the safety glasses or goggles over your eyes, not on top of your head. For certain experiments, full face protection may be necessary.
- If you must wear contact lenses in the laboratory, be extra careful; whether or not you wear contact lenses, do not touch your eyes without first washing your hands. If you do wear contact lenses, make sure that your teacher is aware of it, and you must wear the same eye protection as the rest of the class. Carry your lens case and a pair of glasses with you.
- If you wear prescription eyeglasses, you must still wear the appropriate eye protection on top of them.
- Always stand up when doing laboratory practical work. Do not sit down.
- Wash your hands with soap and warm water when you finish an investigation, and before you leave the laboratory.
- Never use a mouthpiece that has been in another student's mouth. Always disinfect any equipment that is going in your mouth before you use it.
- Use stands, clamps, and holders to secure any potentially dangerous or fragile equipment that could be tipped over.
- Do not taste any substance in a laboratory.
- Never smell chemicals unless specifically instructed to do so by your teacher. Do not inhale the vapours, or gas, directly from the container.
- Report all accidents immediately.
- Inform your teacher of any spills and follow your teacher's instructions on how to clean up the spill. Clean up all spills, even water spills, immediately.

HANDLING GLASSWARE SAFELY

- Never use glassware that is broken, cracked, or chipped. Give such glassware to your teacher or dispose of it as directed. Do not put the item back into circulation.
- Never pick up broken glassware with your fingers. Use a broom and dustpan.
- Check with your teacher before heating any glassware. Heat glassware only if it is approved for heating.
- Be very careful when cleaning glassware. There is an increased risk of breakage from dropping when the glassware is wet and slippery.
- If you cut yourself, inform your teacher immediately and get appropriate first aid.

USING SHARP INSTRUMENTS SAFELY

- Make sure that your instruments are sharp. Dull cutting instruments require more pressure than sharp instruments and are more likely to slip.
- Always transport a scalpel in a dissection case or box. Never carry the scalpel from one area of the laboratory to another with an exposed blade.
- Always cut away from yourself and others.
- If you cut yourself, inform your teacher immediately and get appropriate first aid.

HEAT SAFETY

- Make sure that heating equipment, such as the burner, hot plate, or electric heater, is secure on the bench and clamped in place when necessary.
- Do not use a laboratory burner near wooden shelves, flammable liquids, or any other item that is combustible.

- Do not allow overheating if you are performing an experiment in a closed area.
- Always assume that hot plates and electric heaters are hot and use protective gloves when handling.
- Do not touch a light source that has been on for some time. It may be hot and can cause burns.
- Where burners or hot plates are being used, never pick up a glass object without first checking the temperature by placing your hand near but not touching it. Glass and metal items that have been heated may not appear to be hot, but can cause burns.
- Never look down the barrel of a laboratory burner.
- Always pick up a burner by its base, never by its barrel.
- Never leave a lighted burner unattended.
- Any metal powder can be explosive. Do not put these in a flame.
- When heating a test tube over a laboratory burner, use a test tube holder and spurt cap. Holding the test tube at an angle, with the open end pointed away from you and others, gently move the test tube back and forth through the flame.
- To heat a beaker, put it on the hot plate and secure with a ring support attached to a utility stand. (Placing a wire gauze under the beaker is optional.)
- Remember to include a cooling time in your experiment plan; do not put away hot equipment.

FIRE SAFETY

To use a burner:

- Tie back long hair and tie back or roll up long sleeves or other loose clothing.
- Secure the burner to a stand using a metal clamp.
- Check that the rubber hose is properly connected to the gas valve.
- Close the air vents on the burner. Use a sparker to light the burner.
- Open the air vents just enough to get a blue flame.
- Control the size of the flame using the gas valve.
- Immediately inform your teacher of any fires. A very small fire in a container may be extinguished by covering the container with a wet paper towel or a ceramic square to cut off the supply of air. Alternatively, sand may be used to smother small fires. A bucket of sand with a scoop should be available in the laboratory.
- Different extinguishers are effective for different classes of fires. The fire classes are outlined in **Table 2**. Fire extinguishers in the laboratory are 2A10BC. They extinguish class A, B, and C fires.

Table 2 Classes of Fires

Class	Description	Firefighting strategy
Class A	• ordinary combustible materials that leave coals or ashes (for example, wood, paper, cloth)	• water or dry chemical extinguishers
Class B	• flammable liquids (for example, gasoline or solvents)	• carbon dioxide or dry chemical extinguishers • do not use water
Class C	• live electrical equipment (for example, appliances, photocopiers, computers, laboratory equipment)	• carbon dioxide or dry chemical extinguishers • do not use water
Class D	• burning metals (for example, sodium, potassium, magnesium, aluminum)	• sand, salt, or graphite • do not use water
Class E	• radioactive substance	• requires special consideration at each site

- If anyone's clothes or hair catch fire, tell the person to drop to the floor and roll. Then use a fire blanket to smother the flames. Never wrap the blanket around a standing person on fire.
- For larger fires, immediately evacuate the area. Call the office or sound the fire alarm. Do not try to extinguish larger fires. As you leave the classroom, make sure that the windows and doors are closed.
- If you use a fire extinguisher, direct the extinguisher at the base of the fire and use a sweeping motion, moving the extinguisher nozzle back and forth across the front of the fire's base.

ELECTRICAL SAFETY

- Do not operate electrical equipment near running water or a large container of water. Water or wet hands should never be near electrical equipment such as a hot plate, a light source, or a microscope.
- Check the condition of electrical equipment. Do not use it if wires or plugs are damaged, or if the ground pin has been removed.
- If using a light source, check that the wires of the light fixture are not frayed, and that the bulb socket is in good shape and well secured to a stand.
- Make sure that electrical cords are not placed where someone could trip over them.

- When unplugging equipment, remove the plug gently from the socket. Do not pull on the cord.
- When using variable power supplies, start at low voltage and increase slowly.

HANDLING ANIMALS, PLANTS, AND OTHER ORGANISMS SAFELY

- Ensure that your teacher is aware of any plant or animal allergies that you have.
- Never bring a plant, animal, or other organism to school without receiving prior permission from your teacher.
- Wear gloves and wash your hands before and after feeding or handling an animal, touching materials from the animal's cage or tank, or handling bacterial cultures.
- When growing micro-organisms, it is important to perform investigations in sterile conditions using sterile equipment to avoid contamination from foreign bacteria.
- Cultures should be grown at room temperature or in the range of 25 to 32 °C. Incubation at 37 °C may encourage the growth of micro-organisms that are capable of living in the human body.
- Bacteria from soils should not be grown because of the possibility of culturing tetanus-causing organisms.
- Spores collected from household locations, such as telephones or bathrooms, should not be cultured in the laboratory. The body can destroy small numbers of these bacteria, but may not be able to cope with large numbers.
- Remains of plants and animals can generally be disposed of in school garbage containers. Fungi and bacterial cultures should be autoclaved or treated with a fungicide or antibacterial soap before disposal.
- All surfaces and equipment used in culturing micro-organisms should be washed with a disinfectant (for example, a solution of bleach).
- Apparatuses used in microbiology should be autoclaved because liquid disinfectants and germicidal agents generally cannot guarantee complete sterilization.
- Wild or sick animals should never be brought into the lab. Dead animals, wild or tame, that have died from unknown causes should also not be brought into the lab.
- Preserved specimens should be removed from the preservative with gloves or tongs and rinsed thoroughly in running water.
- Before going on field trips, become familiar with any dangerous plants and animals that may be common in the area (for example, poison ivy, poisonous snakes).
- Notify your teacher of any medical conditions or allergies that you have that could be affected as a result of exposure to any plants or animals on the field trip.

WASTE DISPOSAL

Waste disposal at school, at home, and at work is a societal issue. Most laboratory waste can be washed down the drain or, if it is in solid form, placed in ordinary garbage containers. However, some waste must be treated more carefully. It is your responsibility to follow procedures and to dispose of waste in the safest possible manner according to your teacher's instructions.

FIRST AID

The following guidelines apply in case of an injury, such as a burn, cut, chemical spill, ingestion, inhalation, or splash in the eyes:

- Always inform your teacher immediately of any injury.
- If the injury is a minor cut or abrasion, wash the area thoroughly. Using a compress (for example, clean paper towels), apply pressure to the cut to stop the bleeding. When bleeding has stopped, replace the compress with a sterile bandage. If the cut is serious, apply pressure and seek medical attention immediately.
- If you get a solution in your eye, quickly use the eyewash or nearest running water. Continue to rinse the eye with water for at least 15 min. Unless you have a plumbed eyewash system, you will also need assistance in refilling the eyewash container. Have another student inform your teacher of the accident. The injured eye should be examined by a doctor.
- If the injury is a burn, immediately immerse the affected area in cold water, or run cold water gently over the burned area. This will reduce the temperature and prevent further tissue damage.
- In case of electric shock, unplug the appliance and do not touch it or the victim. Inform your teacher immediately.
- If a classmate's injury has rendered him/her unconscious, notify your teacher immediately. Your teacher will perform CPR if necessary. Do not administer CPR unless under specific instructions from your teacher. Call the school office and request emergency medical help.

A2 Scientific Inquiry

In our attempts to further our understanding of the natural world, we encounter questions, mysteries, or events that are not readily explainable. To develop explanations, we investigate using scientific inquiry. An important aspect of scientific inquiry is that science is only one of many ways people explore, explain, and come to know the world around them. Scientific inquiry is a multifaceted process that involves the following: identifying questions that can be answered through scientific investigations; using appropriate tools and techniques to gather, analyze, and interpret data; developing descriptions, explanations, predictions, and models using evidence; thinking critically and logically to make the connection between evidence and explanations; recognizing and analyzing alternative explanations and predictions; and communicating scientific procedures and explanations.

The methods used in scientific inquiry depend, to a large degree, on the purpose of the inquiry. There are four common types of scientific inquiry: (1) the controlled experiment, (2) the correlational study, (3) the observational study, and (4) the activity. These types of scientific inquiry require specific skills. The skills are discussed below, followed by a detailed description of how they relate to each of the four types of scientific inquiry.

A2.1 Skills of Scientific Inquiry

Scientific inquiry requires certain skills that are important in the process of conducting an investigation. These skills can be organized into four categories: initiating and planning, performing and recording, analyzing and interpreting, and communicating.

INITIATING AND PLANNING

1. Questioning: Most scientific investigations begin with a question. It is important to ask the right questions. In certain types of scientific inquiry, the question must be testable. This means that it must ask about a possible cause-and-effect relationship. A cause-and-effect relationship is one in which a change in one variable (see #3) causes a change in another variable. A testable question might start in one of the following ways: What causes . . . ? How does . . . affect . . . ? If . . . , what happens to . . . ?
2. Researching: This is a skill that occurs across all four categories of scientific inquiry and includes preparing for research, accessing resources, processing information, and transferring learning. The process involves identifying the type of information that is required, using strategies to locate and access the information, recording the information, synthesizing findings, and formulating conclusions.
3. Identifying variables: Considering the variables involved in an investigation is an important step in designing an effective investigation.

   Variables are any factors that could affect the outcome of an investigation. There are three kinds of variables in a controlled experiment: the manipulated variable, the responding variable, and the controlled variables.

   - The manipulated variable (also known as the independent variable or cause variable) is the variable that is deliberately changed by the investigator.
   - The responding variable (also known as the dependent variable or the effect variable) is the variable that the investigator believes will be affected by a change in the manipulated variable.
   - The controlled variables are variables that may affect the responding variable, but that are held constant so that they cannot affect the responding variable. A controlled experiment is a test of whether (and how) a manipulated variable affects a responding variable. To make the test fair, all other variables that may affect the responding variable are kept constant (unchanging).
4. Hypothesizing: A hypothesis is a predicted answer to the testable question. It proposes a possible explanation based on an already known scientific theory, law, or other generalization.

   A hypothesis may be written in the form of an "If . . . , then . . . because . . ." statement. If the manipulated (independent) variable is changed in a particular way, then we predict that the responding (dependent) variable will change in a particular way, and we provide a theoretical explanation for the prediction. You may create more than one hypothesis from the same testable question. For example,

   > If an air-filled balloon is placed in a freezer and its temperature is decreased, then its volume will decrease because, according to the kinetic molecular theory, atoms and molecules slow down and occupy less space at lower temperatures.

   When you conduct an investigation, your observations do not always support the prediction in your hypothesis. When this happens, you may re-evaluate and modify your hypothesis and design a new experiment.
5. Planning: Planning an inquiry activity involves developing an experimental design, identifying variables, selecting necessary equipment and materials, addressing safety concerns, and writing a step-by-step procedure.

PERFORMING AND RECORDING

1. Conducting an inquiry: As you perform an investigation, follow the steps in the procedure carefully and thoroughly. Check with your teacher if you find that you need to make significant alterations to your procedure. Use all equipment and materials safely, appropriately, and with precision.
2. Making observations: When you conduct an investigation, you should make accurate observations at regular intervals and record them carefully and accurately. Record exactly what you observe. Observations from an experiment may not always be what you expect them to be. Qualitative (descriptive) and quantitative (measured) observations may be made during an investigation. Some observations may also be provided for you during an investigation.

   Quantitative observations are based on measured quantities such as temperature, volume, and mass. They are usually recorded in data tables.

   Qualitative observations describe characteristics that cannot be expressed in numbers, such as texture, smell, and taste. They can be recorded using words, pictures, tables, or labelled diagrams.
3. Collecting, organizing, and recording data: During an investigation, you should collect and record all data and observations, and organize these into formats that are easily interpreted (such as tables and charts).

ANALYZING AND INTERPRETING

1. Analyzing: Analyzing involves looking for patterns and relationships that will help you explain your results and give you new information about the question you are investigating. Your analysis will tell you whether your observations support your hypothesis.
2. Evaluating: It is very important to evaluate the evidence that is obtained through observations and analysis. When evaluating the results of an investigation, here are some aspects you should consider:
   - Experimental design: Were there any problems with the way you planned your experiment? Did you control all the variables except for the manipulated variable?
   - Equipment and materials: Was the equipment adequate? Would other equipment have been better? Was something used incorrectly? Did you have difficulty with a piece of equipment?
   - Skills: Did you have the appropriate skills for the investigation? Did you have to use a skill that you were just beginning to learn?
   - Observations: Did you accurately record all the relevant observations?

COMMUNICATING

1. It is important to share both your process and your results. Other people may want to repeat your investigation, or they may want to use or apply your results in another situation. Your write-up or report should reflect the process of scientific inquiry that you used in your investigation.
2. At this stage, you should be prepared to extend insights and opinions from your findings, suggest areas for further investigation, and relate research findings to the world around you.

In the following sections, we will detail the components of the four types of investigations: controlled experiments, correlational studies, observational studies, and activities.

A2.2 Controlled Experiments

A controlled experiment is an example of scientific inquiry in which a manipulated variable is intentionally changed to determine its effect on a responding variable. All other variables are controlled (kept constant). Controlled experiments are performed when the purpose of the inquiry is to create, test, or use a scientific concept.

The common components of controlled experiments are outlined below. Note that there are normally many cycles through the steps during an actual experiment.

TESTABLE QUESTION

A testable question forms the basis for your controlled experiment. The investigation is designed to answer the question. Controlled experiments are about relationships among variables, so your question could be about the effects on variable A when variable B is changed.

VARIABLES

You must identify all major variables that you will measure and/or control in your investigation. What is the manipulated (independent) variable? What is the responding (dependent) variable? What are the controlled variables?

When conducting a controlled experiment, change only one manipulated variable at a time, holding all the others (except the responding variable) constant. This way, you can assume that the results are caused by the manipulated variable and not by any of the other variables.

HYPOTHESIS/PREDICTION

When formulating a hypothesis, first read the testable question, the experimental design, and the procedure. Then try to identify (and distinguish) the manipulated variable, the responding variable, and the controlled variables. Your hypothesis will be a predicted answer to your testable question accompanied by a theoretical explanation for your prediction.

EXPERIMENTAL DESIGN

The design of a controlled experiment shows how you plan to answer your question. The design outlines how you will change the manipulated variable, measure any variations in the responding variable, and control all the other variables. It is a summary of your plan for the experiment.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials you will use, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection, lab apron, protective gloves, and tongs, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description of how you will perform your investigation. It must be clear enough for someone else to follow and it must explain how you will deal with each of the variables in your investigation. The first step in a procedure usually refers to any safety precautions that need to be addressed, and the last step relates to any cleanup that needs to be done.

OBSERVATIONS

There are many ways you can gather and record observations during your investigation. It is helpful to plan ahead and think about what data you will need to answer the question and how best to record them (for example, data tables, pictures, or labelled diagrams may be helpful). This helps to clarify your thinking about the question posed at the beginning, the variables, the number of trials, the procedure, the materials, and your skills. It will also help you organize your evidence for easier analysis.

ANALYZE AND EVALUATE

You will need to analyze and interpret your observations—this may include graphing your data and analyzing any patterns or trends that may be evident in your graphs. After thoroughly analyzing your observations, you may have sufficient and appropriate evidence to enable you to answer the testable question posed at the beginning of the investigation.

You must evaluate the processes that you followed to plan and perform the investigation. You must also evaluate the outcome of the investigation, which involves evaluating your hypothesis/prediction. You must identify and take into account any sources of error and uncertainty in your measurements.

Finally, compare your hypothesis/prediction with the evidence. Is your hypothesis supported by the evidence?

APPLY AND EXTEND

Reflect on how your investigation relates to the world around you: how can you use what you have learned in everyday life?

REPORTING ON THE INVESTIGATION

Your lab report should describe your planning process and procedure clearly and in enough detail that the reader could repeat the experiment exactly as you performed it. You should present your observations, analysis, and evaluation of your experiment clearly, accurately, and honestly.

A2.3 Correlational Studies

When the purpose of scientific inquiry is to test a suspected relationship between two different variables, but a controlled experiment is not possible, a correlational study is conducted. In a correlational study, the investigator tries to determine whether one variable is affecting another without purposely changing or controlling any of the variables. Instead, variables are allowed to change naturally. It is often difficult to isolate cause and effect in correlational studies. A correlational study requires very large sample numbers and many replications to increase the certainty of the results.

A correlational study does not require experiments or fieldwork; for example, the investigator can use databases prepared by other researchers to find relationships between two or more variables. The investigator can, however, choose to make observations and measurements as well, through fieldwork, interviews, and surveys.

A hypothesis or prediction is not needed in a correlational study. Correlational studies are not intended to establish cause-and-effect relationships. However, the results of a correlational study can be used to formulate a hypothesis about the causal relationship between the variables.

The common components of a correlational study are outlined below. Even though the sequence is presented as linear, there are normally many cycles through the steps during an actual study.

PURPOSE

When planning a correlational study, it is important that you pose a question about a possible statistical relationship between variable A and variable B. Choose a topic that interests you. Determine whether you are going to replicate or revise a previous study, or create a new one. Indicate your decision in the statement of the purpose.

VARIABLES

In a correlational study, you must determine whether two variables are related, without controlling any of the variables. Correlation is the degree to which two sets of data vary together. You must identify all the major variables that will be measured and/or observed in your investigation.

STUDY DESIGN

When designing your correlational study, you must identify the setting and the methods you will use in carrying out your investigation. You should describe the type(s) of data you plan to collect and their sources. Your design should address questions such as the following: Will you be conducting a survey? If so, where will the survey be conducted? Who will answer your survey? When will the survey be conducted? How often will the survey be administered? If you are obtaining information from an existing database, then describe the source of the information and your plans for analyzing the information.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection and ear protection, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description identifying how you will gather data on the variables under study. You will also need to identify potential sources of data. There are two possible sources: observations made by you, the investigator, and existing data (databases, for example).

OBSERVATIONS

If you are collecting your own data through observation, then you will need to plan ahead and think about what data you will need and how best to record them. There are many ways to gather and record your observations (such as data tables, pictures, or labelled diagrams). This is an important step because it helps to clarify your thinking about the question posed at the beginning, the variables, the procedure, the materials, and your skills. It will also help you organize your observations for easier analysis.

ANALYZE AND EVALUATE

You will need to analyze and interpret your observations or sourced data—this will usually include graphing the data and analyzing any patterns or trends that may be evident in your graphs. You will need to identify the relationship between your two variables. A positive correlation indicates a direct relationship between variables: an increase in one variable corresponds to an increase in another (**Figure 1(a)**). A negative correlation indicates an inverse relationship: an increase in one variable corresponds to a decrease in the other variable (**Figure 1(b)**). If there is no relationship between the variables, then there is no correlation (**Figure 1(c)**).

When you know that two variables are correlated, you can predict one variable based on the other. Generally, the stronger the correlation, the more probable it is that your prediction will be correct. After analyzing your observations, revisit the question you posed at the beginning of the investigation. Is there a relationship between variable A and variable B?

Evaluate the processes that you followed to plan and perform the investigation. Also evaluate the outcome of the investigation, which involves evaluating any prediction you made at the beginning of the investigation. You must identify and take into account any sources of error and uncertainty in your measurements.

APPLY AND EXTEND

Reflect on how your investigation relates to the world around you: how can you use what you have learned in your everyday life?

REPORTING ON THE INVESTIGATION

In preparing your report, your objectives should be to describe your design and procedure accurately and to report your observations, analyses, and evaluations accurately and honestly.

A2.4 Observational Studies

Often, the purpose of an inquiry is simply to study a natural phenomenon with the intention of gaining scientifically significant information to answer a question. Observational studies involve observing a subject or phenomenon in an unobtrusive or unstructured manner, usually with no specific hypothesis. The inquiry does not start off with a hypothesis, but a hypothesis may be generated as information is collected.

The stages and processes of scientific inquiry through observational studies are summarized on the next page. Even though the sequence is presented as linear, there are normally many cycles through the steps during an actual study.

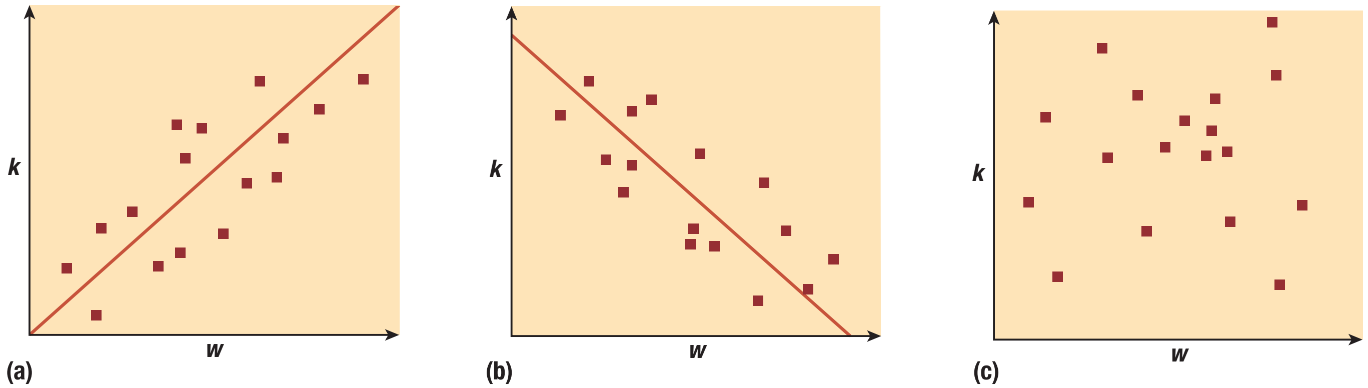


Figure 1 (a) In a positive correlation, variable *k* increases as variable *w* increases. (b) In a negative correlation, *k* decreases as *w* increases. (c) If there is no correlation, there is no pattern.

PURPOSE

In planning an observational study, it is important to pose a general question about the natural world. Choose a topic that interests you. Determine whether you are going to replicate or revise a previous study, or create a new one. Indicate your decision in a statement of the purpose.

EQUIPMENT AND MATERIALS

Make a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Write a step-by-step description of how you will make your observations. The first step in a procedure usually refers to any safety precautions that need to be addressed, and the last step relates to any cleanup that needs to be done.

OBSERVATIONS

There are many ways you can gather and record observations—including quantitative observations—during an observational study. All observations should be objective. Consider ways to organize your information for easier analysis.

ANALYZE AND EVALUATE

After thoroughly analyzing your observations, you may have sufficient and appropriate evidence to enable you to answer the question posed at the beginning of the investigation. You may also have enough observations and information to form a hypothesis for a controlled experiment.

At this stage of the investigation, you will evaluate the processes used to plan and perform the investigation. Evaluating the processes includes evaluating the materials, the design, the procedure, and your skills. The results of most such investigations will suggest further studies, perhaps controlled experiments or correlational studies, to explore tentative hypotheses you may have developed.

APPLY AND EXTEND

At this stage, you should reflect on how your investigation relates to the world around you: how can you use what you have learned in your everyday life?

REPORTING ON THE INVESTIGATION

In your report, describe your design and procedure accurately, and report your observations accurately and honestly.

A2.5 Activities

An activity is a type of scientific inquiry that provides opportunities for you to demonstrate your knowledge and understanding of a specific concept. An activity might involve constructing a device, reasoning your way through a problem (a thought experiment), or using given information to complete a task. You might be asked to consider creative ways to present the concept, such as a performance, a digital platform, or a written report. The materials that are required for different activities can vary greatly, so materials may need special planning and attention. Activities do not have structured stages and processes. However, to demonstrate a thorough understanding of the concept, you will need to communicate the key points. You will need to analyze and evaluate your presentation, which may include looking at how your understanding of the concept has grown and applying what you have learned to other areas.

A2.6 Lab Reports

When carrying out investigations, it is important that scientists keep records of their plans and results, and share their findings. In order to have their investigations repeated (replicated) and accepted by the scientific community, scientists generally share their work by publishing reports in which details of their design, materials, procedure, evidence, analysis, and evaluation are provided.

Lab reports are prepared after an investigation is completed. To ensure that you can accurately describe the investigation, keep thorough and accurate records of your activities as you carry out the investigation.

Your lab book or report should reflect the type of scientific inquiry that you used in the investigation (controlled experiment, correlational study, observational study, or activity) and should be based on the following headings, *as appropriate*:

TITLE

At the beginning of your report, write the number and title of your investigation. If you are designing your own investigation, create a title that suggests what the investigation is about. Include the date the investigation was conducted and the names of all lab partners.

PURPOSE

State the purpose of the investigation. Why are you doing this investigation?

TESTABLE QUESTION

State the question that you attempted to answer in the investigation. Sometimes the question is provided for you; other times you are expected to formulate your own. If it is appropriate to do so, state the question in terms of manipulated and responding variables.

HYPOTHESIS/PREDICTION

For a controlled experiment, you will usually have to compose a hypothesis or prediction. This will be a proposed answer to your testable question. When writing a hypothesis, include both a prediction and a reason for the prediction, based on scientific theory, law, or other generalization. You may use the "If . . . , then . . . because . . ." form. A simple prediction may be written in the "If . . . , then . . ." form.

VARIABLES

Identify all major variables that you measured and/or controlled in the investigation. What is the manipulated variable? What is the responding variable? What are the major controlled variables?

EXPERIMENTAL DESIGN

Provide a brief general overview (one to three sentences) of what you did in your investigation. If your investigation involved manipulated, responding, and controlled variables, list them and indicate how they were changed, measured, or held constant. Identify any control or control group that was used in the investigation.

EQUIPMENT AND MATERIALS

Include a detailed list of all equipment and materials used, including sizes and quantities where appropriate. Be sure to include safety equipment, such as eye protection, lab apron, protective gloves, and tongs, where needed. Draw a diagram to show any complicated setup of apparatus.

PROCEDURE

Describe, in detailed numbered steps, the procedure you followed to carry out your investigation. Your teacher may specify which style you should use. Examples of three common writing styles are

1. passive tense ("The test tubes were heated . . .")
2. first person plural past tense ("We heated the test tubes . . .")
3. second person imperative ("Heat the test tubes . . .")

Include steps to clean up and dispose of waste.

OBSERVATIONS

Present your observations in a form that is easily understood. This includes all the qualitative and quantitative observations that you made. Be as precise as possible when describing quantitative observations. Include any unexpected observations and present your information clearly. If you have only a few observations, this could be a list; for controlled experiments and for many observations, a data table, labelled diagram, or written descriptions would be more appropriate.

ANALYSIS

Complete the questions found in the Analyze and Evaluate section of the investigation. These questions will prompt you to analyze and interpret your observations, answer a testable question, draw conclusions, and evaluate both your experiment and your conclusions. You will also be prompted to graph your data and analyze these graphs where applicable.

If you are writing up an investigation for which there are no questions, write your own analysis. Interpret your observations and present the evidence in the form of titled tables, graphs, or illustrations, as appropriate. Include any calculations, the results of which can be shown in a table. Make statements about any patterns or trends you observed. Conclude the analysis with a statement based only on the evidence you have gathered, answering the question that initiated the investigation.

EVALUATION

The evaluation is your judgment about the quality of evidence obtained and about the validity of the prediction and hypothesis (if present). This section can be divided into two parts:

1. Evaluation of the experiment: Did your experiment provide reliable and valid evidence to enable you to answer the question? Consider the experimental design, the procedure, and your laboratory skills. Were they all adequate? Are you confident enough in the evidence to use it to evaluate any prediction and/or hypothesis you made?
2. Evaluation of the prediction: Was the prediction you made before the investigation supported or falsified by the evidence? Based on your evaluation of the evidence and prediction, is the hypothesis you used to make your prediction supported, or should it be rejected?

APPLY AND EXTEND

Answer any Apply and Extend questions in the investigation. Number your answers as they appear in the Apply and Extend section in the textbook.

A3 Scientific Publications

Communicating in Science

Advances in science and our understanding of the natural world are the result of scientists sharing ideas and information. Watson and Crick won the Nobel Prize for discovering the double helix structure of DNA, but they solved this structure with the help of X-ray photographs taken by Rosalind Franklin during her own research.

It is important for scientists to share ideas and research with other scientists. New research findings are shared at conferences or in journal publications. Research scientists take pride in being published. Being published confirms that the research adds to the knowledge base of the scientific community. Sharing information helps to spread knowledge, solve problems, and inspire other scientists.

The Scientific Journal

Scientific journals are publications that are used to present new research. There are thousands of different science journals published worldwide, and in many languages. A scientific journal may be specific to a subject (for example, *Canadian Journal of Diabetes*) or contain articles that cover a variety of subjects within a field (for example, *Nature*). These publications may be electronic (online) or in print and may be published weekly, monthly, bimonthly, or quarterly.

Peer Review

When an article is submitted to a journal, the research findings are critically reviewed by experts in that subject or field. This ensures that the research presents ideas that are supported by practices of good science. High-quality evidence and appropriate conclusions are necessary for the article to be accepted for publication. An article that is submitted to a reputable journal may take months to be approved for publication. The article may be returned to the author(s) for revision if necessary.

Scientists aim to be published in the most respected journals. The peer-review process contributes to the reputation of a journal. It helps to maintain standards and provide credibility. A scientific journal becomes reputable by ensuring that only articles of high quality are published. Very prestigious journals (such as *Nature, Science*, and *New England Journal of Medicine*) are known for publishing research backed by only the best practices of science. Reputable journals are widely read and considered reliable by the scientific community. Publication in a reputable journal brings immediate recognition for the author(s). Research that is not published in a peer-reviewed journal is often overlooked or disregarded.

Format of Research Articles

Research articles have specific sections. Articles often include an abstract, introduction, methods, results, discussion, conclusions, and references. Go to the Nelson Science website to see an example of a real research article with a description of each section. WEB LINK

THE ABSTRACT

The abstract is a short summary of the article. It presents the purpose of the research, outlines the design of the experiment and methods used, and summarizes findings or conclusions. A well-written abstract is useful when looking for articles with specific information. Time may be saved by reading the abstract and then deciding if the article will be helpful in supporting research. The background material, methods used, results, main subject, and discussion are all summarized within the abstract.

CITING SOURCES AND GIVING CREDIT

Once a scientist has found useful sources and included them in an article or paper, information must be provided about the sources so that someone else who is interested in learning more will be able to find them. This also shows the reader that information supporting the research is current.

More importantly, citing another scientist's work provides a measure of value of what he or she has published. It gives credit to the scientist. More citations often mean that the work is worthwhile and influential. An example of this is the frequency of citation of Kary Mullis's work that presented the polymerase chain reaction (PCR)—an important advance in genetics for copying DNA fragments. Thousands of citations occurred within a few years of publication, confirming that his work was influential.

Further Reading

Day, R.A., & Gastel, B. (2006). *How to write and publish a scientific paper* (6th ed.). Cambridge: Cambridge University Press.

Frame, P.F., Hik, D.S., Cluff, H.D., & Paquet, P.C. (June 2004). Long foraging movement of a denning tundra wolf. *Arctic*, 57 (2), 196–203.

WEB LINK

A4 Exploring Issues and Applications

Throughout this textbook, you will have many opportunities to examine the connections between science, technology, society, and the environment (STSE) by exploring issues and applications.

An issue is a situation in which several points of view need to be considered in order to make a decision. There can be many positions, generally determined by the values that an individual or a society holds, on a single issue. Which solution is “best” is a matter of opinion; ideally, the solution that is implemented is the one that is most appropriate for society as a whole. Researching information about an issue will help you make an educated decision about it. All the skills listed in Section A4.1 may be useful in an activity that involves exploring an issue.

Scientific research produces knowledge or understanding of natural phenomena. Technologists and engineers look for ways to apply this knowledge in the development of practical products and processes. Technological inventions and innovations can have wide-ranging applications for, and impacts on, society and the environment. The purpose of exploring an application is to research a particular technological invention or innovation to determine how it works, how it is used, and how it may affect society and the environment. The skills of researching, communicating, and evaluating may be useful in an activity that involves exploring an application.

A4.1 Research Skills

The following skills are involved in many types of research. Some of these skills will help you research issues only, while some will help you research issues or applications. Refer to this section when you have questions about any of the following skills and processes.

DEFINING THE ISSUE

When exploring an issue, the first step in understanding the issue is to explain why it exists; the problems associated with it; and, if applicable, the individuals or groups, also known as stakeholders, that are involved in it. The issue includes information about the role you will take when thinking about an issue, as well as a description of who your audience will be. You could brainstorm questions involving Who? What? Where? When? Why? and How? Develop background information on the issue by clarifying facts and concepts and identifying relevant attributes, features, or characteristics of the problem.

RESEARCHING

When beginning your research for both issues and applications, you need to formulate a research question that helps to limit, narrow, or define the scope of your research. You then need to develop a plan to find reliable and relevant sources of information. This includes outlining the stages of your research: gathering, sorting, evaluating, selecting, and integrating relevant information. You should gather information from a variety of sources if possible (for example, print, web, and personal interviews).

As you collect information, do your best to ensure that the information is reliable, accurate, and current. Avoid biased opinions: those that are not supported by or that ignore credible evidence. It is important to ensure that the information you have gathered addresses all aspects of the issue or application you are researching.

IDENTIFYING ALTERNATIVES

When exploring an issue, examine the situation and think of as many alternative solutions as you can. Be creative about combining the solutions. At this point, it does not matter if the solutions seem unrealistic. To analyze the alternatives, you should examine the issue from a variety of perspectives. Stakeholders may bring different viewpoints to an issue, and these may influence their position on the issue. Brainstorm or hypothesize how different stakeholders would feel about your alternatives.

ANALYZING THE ISSUE

An important part of exploring an issue is analyzing the issue. First, you should establish criteria for evaluating your information to determine its relevance and significance. You can then evaluate your sources, determine what assumptions may have been made, and assess whether you have enough information to make your decision.

To effectively analyze an issue, you should

- establish criteria for determining the relevance and significance of the data you have gathered
- evaluate the sources of information
- identify and determine what assumptions have been made
- challenge unsupported evidence
- evaluate the alternative solutions, possibly by conducting a risk–benefit analysis

Once the issue has been analyzed, you can begin to evaluate the alternative solutions. You may decide to carry out a risk–benefit analysis—a tool that enables you to look at each possible result of a proposed action and helps you make a decision (see Section A4.2 for more information.)

DEFENDING A DECISION

After analyzing your information on your issue, you can answer your research question and take an informed position or draw a conclusion on the issue. If you are working as a group, this is the stage where everyone gets a chance to share ideas and information gathered about the issue. Then the group needs to evaluate all the possible alternatives and decide on their preferred solution based on the criteria.

Your position on the issue or conclusion must be justified using supporting information that you have researched. You should be able to defend your position to people with different perspectives. Ask yourself the following questions:

- Do I have supporting evidence from a variety of sources?
- Can I state my position clearly?
- Can I show why this issue is relevant and important to society?
- Do I have solid arguments (with solid evidence) supporting my position?
- Have I considered arguments against my position and identified their faults?
- Have I analyzed the strong and weak points of each perspective?

COMMUNICATING

When exploring an issue, there are several things to consider when communicating your decision. You need to state your position clearly and take into consideration who your audience is. You should always support your decision with objective data and a persuasive argument if possible. Be prepared to defend your position against any opposition.

You should be able to defend your solution in an appropriate format—debate, class discussion, speech, position paper, multimedia presentation, brochure, poster, video, etc.

When exploring an application, you should communicate the "need or want" for the application (why the application was developed in the first place); the "how" (how the application actually works); and the risks and benefits to society, individuals, and the environment. You should conclude with your "assessment" of the application.

EVALUATING

The final phase of your decision-making when exploring an issue includes evaluating the decision itself and the process used to reach the decision. After you have made a decision, carefully examine the thinking that led to your decision.

Some questions to guide your evaluation are the following:

- What was my initial perspective on the issue? How has my perspective changed since I first began to explore the issue?
- How did I make my decision? What process did I use? What steps did I follow?
- To what extent were my arguments factually accurate and persuasively made?
- In what ways does my decision resolve the issue?
- What are the likely short- and long-term effects of the decision?
- To what extent am I satisfied with the final decision?
- What reasons would I give to explain my decision?
- If I had to make this decision again, what would I do differently?

A4.2 Risk–Benefit Analysis Model

Risk–benefit analysis is a tool used to organize and analyze information gathered in research, especially when exploring a socio-scientific issue. A thorough analysis of the risks and benefits associated with each alternative solution can help you decide on the best alternative.

- Research as many aspects of the situation as possible. Look at it from different perspectives.
- Collect as much evidence as you can, including reasonable projections of likely outcomes if the proposal is adopted.
- Classify every individual potential result as being either a benefit or a risk.
- Quantify the size of the potential benefit or risk (perhaps as a dollar figure, or a number of lives affected, or on a scale of 1 to 5).
- Estimate the probability (percentage) of that event occurring.
- By multiplying the size of a benefit (or risk) by the probability of its happening, you can calculate a probability value for each potential result.
- Total the probability values of all the potential risks and all the potential benefits.
- Compare the sums to help you decide whether to accept the proposed action.

A5 Math Skills

A5.1 Scientific Notation

It is difficult to work with very large or very small numbers when they are written in common decimal notation. Usually it is possible to accommodate such numbers by changing the SI prefix so that the number falls between 0.1 and 1000. For example, 237 000 000 mm can be expressed as 237 km, and 0.000 000 895 kg can be expressed as 0.895 mg. However, this prefix change is not always possible, either because an appropriate prefix does not exist or because it is essential to use a particular unit of measurement in a calculation. In these cases, the best method of dealing with very large and very small numbers is to write them using scientific notation. Scientific notation expresses a number by writing it in the form $a \times 10^n$, where $1 < |a| < 10$ and the digits in the coefficient a are all significant. **Table 1** shows situations where scientific notation would be used.

Table 1 Examples of Scientific Notation

Expression	Common decimal notation	Scientific notation
"124.5 million kilometres"	124 500 000 km	1.245×10^8 km
"154 thousand picometres"	154 000 pm	1.54×10^5 pm (or 1.54×10^{-7} m)
"602 sextillion molecules"	602 000 000 000 000 000 000 000 molecules	6.02×10^{23} molecules

To multiply numbers in scientific notation, multiply the coefficients and add the exponents. To divide numbers in scientific notation, divide the coefficients and subtract the exponents. The answer is always expressed in scientific notation. Note that the coefficient should always be between 1 and 10. For example,

$$\begin{aligned}(4.73 \times 10^5 \text{ m})(5.82 \times 10^7 \text{ m}) &= 27.5 \times 10^{12} \text{ m}^2 \\ &= 2.75 \times 10^{13} \text{ m}^2\end{aligned}$$

$$\frac{(6.4 \times 10^6 \text{ m})}{(2.2 \times 10^3 \text{ s})} = 2.9 \times 10^3 \text{ m/s}$$

When evaluating exponents, the following rules apply:

$$x^a \cdot x^b = x^{a+b} \qquad (xy)^b = x^b y^b$$

$$\frac{x^a}{x^b} = x^{a-b} \qquad \left(\frac{x}{y}\right)^b = \frac{x^b}{y^b}$$

$$(x^a)^b = x^{ab}$$

SCIENTIFIC NOTATION WITH CALCULATORS

On many calculators, scientific notation is entered using a special key, labelled EXP or EE. This key includes "× 10" from the scientific notation; you need to enter only the exponent. For example, to enter

7.5×10^4 press 7.5 EXP 4
3.6×10^{-3} press 3.6 EXP +/−3

Depending on the type of calculator you have, +/− may need to be entered after the relevant number.

A5.2 Uncertainty in Measurements

There are two types of quantities that are used in science: exact values and measurements. Exact values include defined quantities (1 m = 100 cm) and counted values (5 beakers or 10 trials). Measurements, however, are not exact because there is some uncertainty or error associated with every measurement.

SIGNIFICANT DIGITS

The certainty of any measurement is communicated by the number of significant digits in the measurement. In a measured or calculated value, significant digits are the digits that are known reliably, or for certain, and include the last digit that is estimated or uncertain. Significant digits include all digits correctly reported from a measurement.

Follow these rules to decide if a digit is significant:

1. All non-zero digits are significant.
2. If a decimal point is present, zeros to the left of other digits (leading zeros) are not significant.
3. If a decimal point is not present, zeros to the right of the last non-zero digit (trailing zeros) are not significant.
4. Zeros placed between other digits are always significant.
5. Zeros placed after other digits to the right of a decimal point are significant.
6. When a measurement is written in scientific notation, all digits in the coefficient are significant.
7. Counted and defined values have infinite significant digits.

Table 2 shows examples of significant digits.

Table 2 Certainty in Significant Digits

Measurement	Number of significant digits
32.07 m	4
0.0041 g	2
5×10^5 kg	1
7002 N • m	4
6400 s	2
6.0000 A	5
204.0 cm	4
10.0 kJ	3
100 people (counted)	infinite

An answer obtained by multiplying and/or dividing measurements is rounded to the same number of significant digits as the measurement with the fewest significant digits. For example, using a calculator to solve the following equation,

$$77.8 \text{ km/h} \times 0.8967 \text{ h} = 69.76326 \text{ km}$$

However, the certainty of the answer is limited to three significant digits, so the answer is rounded up to 69.8 km. The same applies to scientific notation. For example,

$$(5.5 \times 10^4) \times (4.236 \times 10^4) = 2.3 \times 10^9$$

ROUNDING

When adding or subtracting measurements of different precisions, the answer is rounded to the same precision as the least precise measurement. For example, using a calculator,

$$11.7 \text{ cm} + 3.29 \text{ cm} + 0.542 \text{ cm} = 15.532 \text{ cm}$$

The answer must be rounded to 15.5 cm because the first measurement limits the precision to a tenth of a centimetre.

Follow these rules to round answers to calculations:

1. When the first digit to be dropped is 4 or less, the last digit retained should not be changed.

   3.141 326 rounded to 4 digits is 3.141
2. When the first digit to be dropped is greater than 5, or if it is a 5 followed by at least one digit other than zero, the last digit retained is increased by 1 unit.

   2.221 682 rounded to 5 digits is 2.2217

   4.168 501 rounded to 4 digits is 4.169
3. When the first digit discarded is 5 followed by only zeros, the last digit retained is increased by 1 if it is odd, but not changed if it is even.

   2.35 rounded to 2 digits is 2.4

   2.45 rounded to 2 digits is 2.4

   −6.35 rounded to 2 digits is −6.4

MEASUREMENT ERROR

There are two types of measurement error: random error and systematic error. Random error results when an estimate is made to obtain the last significant digit for any measurement. The size of the random error is determined by the precision of the measuring instrument. For example, when measuring length with a measuring tape, it is necessary to estimate between the marks on the measuring tape. If these marks are 1 cm apart, the random error will be greater and the precision will be less than if the marks are 1 mm apart. Such errors can be reduced by taking the average of several readings.

Systematic error is associated with an inherent problem with the measuring system, such as the presence of an interfering substance, incorrect calibration, or room conditions. For example, if a balance is not zeroed at the beginning, all measurements will have a systematic error; using a slightly worn metre stick will also introduce a systematic error. Such errors are reduced by adding or subtracting the known error, calibrating the instrument, or performing a more complex investigation.

PRECISION AND ACCURACY

Precision and accuracy are two other terms used to describe how close a measurement is to a true value. The precision of a measurement depends upon the gradations of the measuring device. Precision is the place value of the last measurable digit. For example, a measurement of 12.74 cm is more precise than a measurement of 127.4 cm because the first value was measured to hundredths of a centimetre, whereas the latter was measured to tenths of a centimetre.

No matter how precise a measurement is, it still may not be accurate. Accuracy refers to how close a value is to its accepted value. An accurate measurement has a low uncertainty. **Figure 1** shows an analogy between precision and accuracy: the positions of golf balls on a golf course.

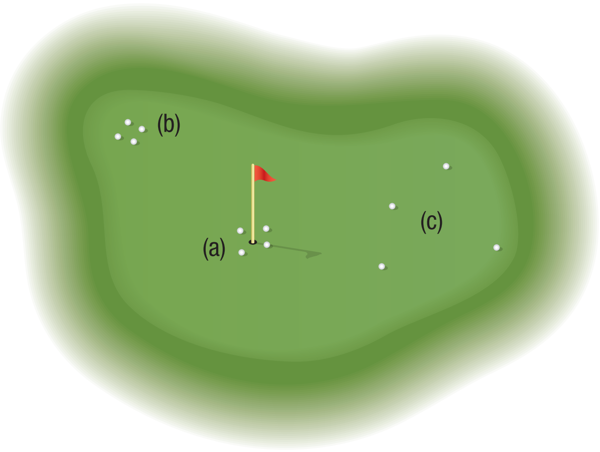


Figure 1 In (a) the results are precise and accurate, in (b) they are precise but not accurate, and in (c) they are neither precise nor accurate.

How certain you are about a measurement depends on two factors: the precision of the instrument used and the size of the measured quantity. More precise instruments give more certain values. For example, a mass measurement of 13 g is less precise than a measurement of 12.76 g; you are more certain about the second measurement than the first. Certainty also depends on the size of the measurement. For example, consider the measurements 0.4 cm and 15.9 cm; both have the same precision. However, if the measuring instrument is precise to ± 0.1 cm, the first measurement is 0.4 ± 0.1 cm (0.3 cm or 0.5 cm) for an error of 25 %, whereas the second measurement could be 15.9 ± 0.1 cm (15.8 cm or 16.0 cm) for an error of 0.6 %. For both factors—the precision of the instrument used and the value of the measured quantity—the more digits there are in a measurement, the more certain you are about the measurement.

REPORTING DATA INVOLVING MEASUREMENTS

A formal report of an experiment involving measurements should include an analysis of uncertainty, percentage uncertainty, and percentage error or percentage difference. Uncertainty is often assumed to be plus or minus half of the smallest division of the scale on the instrument; for example, the estimated uncertainty of 15.8 cm is ± 0.05 cm or ± 0.5 mm.

Whenever calculations involving addition or subtraction are performed, the uncertainties accumulate. Thus, to find the total uncertainty, the individual uncertainties must be added. For example,

$$\begin{aligned}&(34.7\text{ cm} \pm 0.05\text{ cm}) - (18.4\text{ cm} \pm 0.05\text{ cm})\\ &\qquad = 16.3\text{ cm} \pm 0.10\text{ cm}\end{aligned}$$

Percentage uncertainty is calculated by dividing the uncertainty by the measured quantity and multiplying by 100. Use your calculator to prove that 28.0 cm ± 0.05 cm has a percentage uncertainty of ± 0.18 %.

Whenever calculations involving multiplication or division are performed, the percentage uncertainties must be added. If desired, the total percentage uncertainty can be converted back to uncertainty. For example, consider the area of a certain rectangle:

$$\begin{aligned}A &= lw\\ &= (28.0\text{ cm} \pm 0.18\ \%)(21.5\text{ cm} \pm 0.23\ \%)\\ &= 602\text{ cm}^2 \pm 0.41\ \%\\ A &= 602\text{ cm}^2 \pm 2.5\text{ cm}^2\end{aligned}$$

Percentage error can be determined only if it is possible to compare a measured value with that of the most commonly accepted value. The equation is

$$\%\text{ error} = \frac{\text{measured value} - \text{accepted value}}{\text{accepted value}} \times 100$$

Percentage difference is useful for comparing two measurements when the true measurement is not known or for comparing a measured value to a predicted value. The percentage difference is calculated as

$$\%\text{ difference} = \frac{\text{measured value} - \text{predicted value}}{\text{predicted value}} \times 100$$

A5.3 Probability

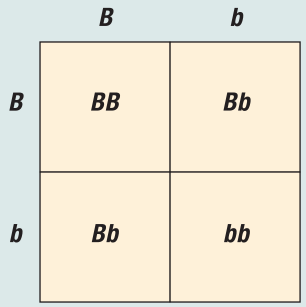
In scientific investigations, probability is a measure of the likelihood of a specific event occurring and is usually expressed as a number between 0 and 1. A probability of 0 means the event will not occur; a probability of 1 means the event will definitely occur. Probabilities may also be expressed as fractions or as percentage.

There are two types of probability: theoretical probability and experimental probability. Theoretical probability is the likelihood of an event occurring based on the information known about certain conditions. This is an expectation.

$$\text{theoretical probability} = \frac{\text{number of desired outcomes}}{\text{total number of possible outcomes}}$$

Example 1

Black fur colour is a dominant trait in guinea pigs, while white fur colour is a recessive trait. What is the theoretical probability of a pair of heterozygous black guinea pigs (*Bb*) producing offspring with white fur (*bb*)? Using a Punnett square (**Figure 2**), we show that if four offspring were produced, it is expected that three would have black fur and one would have white fur.



	B	***b***
B	***BB***	***Bb***
b	***Bb***	***bb***

Figure 2 Punnett square showing a $Bb \times Bb$ cross

$$\begin{aligned}\text{theoretical probability} &= \frac{\text{number of desired outcomes}}{\text{total number of possible outcomes}}\\ &= \frac{\text{number of offspring with white fur}}{\text{total number of possible outcomes}}\\ &= \frac{1}{4}\\ &= 0.25\\ &= 25\ \%\end{aligned}$$

The theoretical probability of producing white offspring is $\frac{1}{4}$ or 25 %. So if a litter had eight offspring, then you could expect two to have white fur.

Experimental probability is based on the recorded outcomes or events of an investigation. The more often an experiment is repeated or the more observations made, the closer the experimental probability will be to the theoretical probability.

$$\text{experimental probability} = \frac{\text{number of desired outcomes observed}}{\text{total number of observations}}$$

Example 2

Black fur colour is a dominant trait in guinea pigs, while white fur colour is a recessive trait. Two heterozygous black guinea pigs (*Bb*) were crossed. The litter contained six offspring with black fur and one with white fur. What is the experimental probability of producing offspring with white fur?

$$\begin{aligned}\text{experimental probability} &= \frac{\text{number of desired outcomes observed}}{\text{total number of observations}}\\ &= \frac{\text{number of offspring with white fur}}{\text{total number of possible offspring}}\\ &= \frac{1}{7}\\ &= 0.14\\ &= 14\ \%\end{aligned}$$

The experimental probability of having offspring with white fur is 14 %. If you performed the same analysis on a large number of litters, you would expect the experimental probability to be the same as (or very close to) the theoretical probability.

A5.4 Graphs

There are many types of graphs that you can use to organize your data. You need to identify which type of graph is best for your data before you begin graphing. Three of the most useful kinds are bar graphs, circle (pie) graphs, and point-and-line graphs.

BAR GRAPHS

When at least one of the variables is qualitative, use a bar graph to organize your data (**Figure 3**). For example, a bar graph would be a good way to present the data collected from a study of the number of plants (quantitative) and the type of plants found (qualitative) in a local nursery. In this graph, each bar stands for a different category, in this case a type of plant.

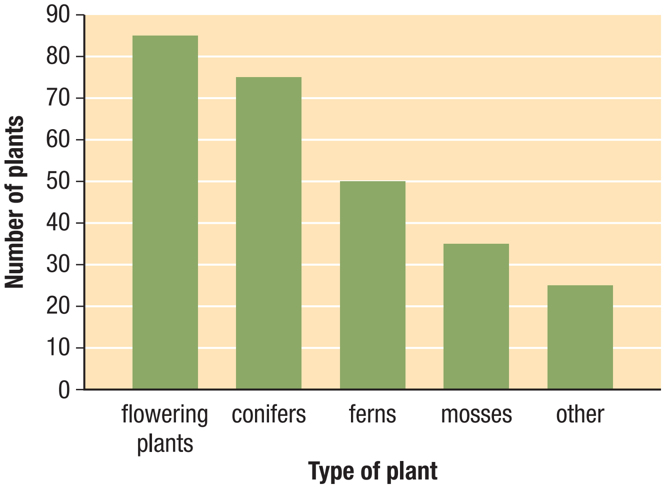


Figure 3 Bar graph

CIRCLE GRAPHS

A circle graph is used if the quantitative variable can be changed to a percentage of a total quantity (**Figure 4**). For example, if you surveyed a local nursery to determine the types of plants found and the number of each, you could make a circle graph. Each piece in the graph stands for a different category (for example, the type of plant). The size of each piece is determined by the percentage of the total that belongs in each category (for example, the percentage of plants of a particular type).

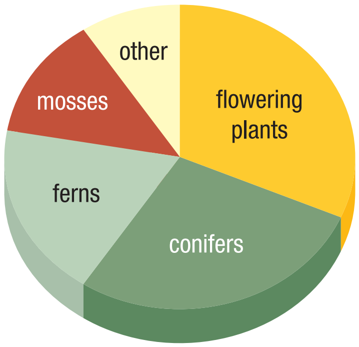


Figure 4 Circle graph

POINT-AND-LINE GRAPHS

When both variables are quantitative, use a point-and-line graph. For example, you can use the following guidelines and the data in **Table 3** to construct a point-and-line graph.

Table 3 Number of Brine Shrimp Eggs Hatched in Salt Solutions of Various Concentrations

Day	2 % salt	4 % salt	6 % salt	8 % salt
1	0	0	0	1
2	0	11	2	3
3	0	14	8	5
4	2	20	17	8
5	5	37	25	15
6	6	51	37	31

1. Use graph paper and construct your graph on a grid. The horizontal edge on the bottom of this grid is the *x*-axis and the vertical edge on the left is the *y*-axis. Do not be too thrifty with graph paper—a larger graph is easier to interpret.
2. Decide which variable goes on which axis and label each axis, including the units of measurement. The independent variable is generally plotted along the *x*-axis and the dependent variable along the *y*-axis.

3. Title your graph. The title should be a concise description of the data contained in the graph.
4. Determine the range of values for each variable. The range is the difference between the largest and smallest values. Graphs often include extra length on each axis, to make them appear less cramped.
5. Choose a scale for each axis. This will depend on how much space you have and the range of values for each axis. Each line on the grid usually increases steadily in value by a convenient number, such as 1, 2, 5, 10, 50, or 100.
6. Plot the points. Start with the first pair of values, which may or may not be at the origin of the graph.
7. After all the points are plotted, draw a line through the points to show the relationship between the variables, if possible. Not all points may lie exactly on a line; small errors in each measurement may have occurred and moved the points away from the perfect line. Draw a line that comes closest to most of the points. This is called the line of best fit—a smooth line that passes through or between the points so that there are about the same number of points on each side of the line. The line of best fit may be straight or curved (**Figure 5**). Graphs often use different colours or symbols to indicate the different sets, and include a legend. In some cases, you may prefer to join the dots when graphing values that are counted rather than measured.

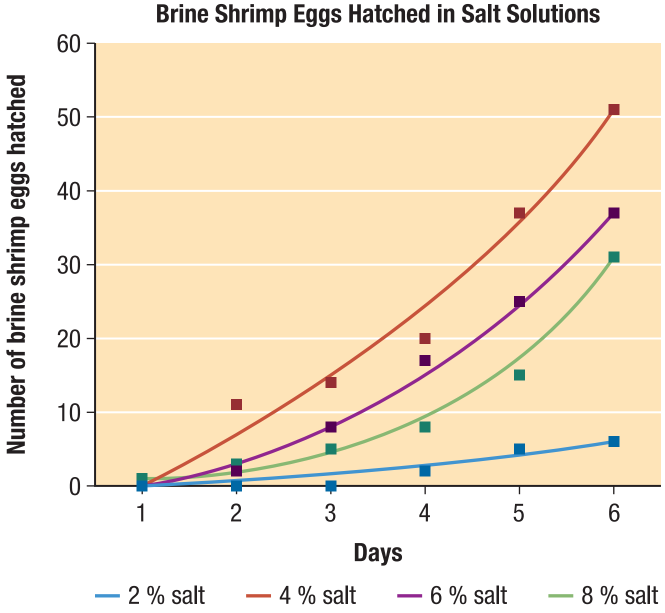


Figure 5 Point-and-line graph

A6 Choosing Appropriate Career Pathways

One of the most difficult tasks in high school is deciding what career path to follow after graduation. The science skills and concepts presented in this book will be of benefit to many careers, whether you are planning a career in scientific research (such as research geneticist or astrophysicist) or in areas related to science (such as environmental lawyer, pharmaceutical sales rep, or electrician). The strong critical-thinking and problem-solving skills that are emphasized in science programs are a valuable asset for any career.

Career Links and Pathways

Throughout this textbook, you will have many opportunities to explore careers related to your studies in Biology. The Career Links icons found at the ends of some paragraphs indicate that you can learn more about these careers on the Nelson Science website. At the end of each chapter, you will also find a Career Pathways feature that illustrates educational pathways for some of the careers mentioned.

It is wise to begin researching academic requirements as early as possible. Understanding the options available to pursue a particular career will help you make decisions on whether to attend university or college, and which program of study you should take. In addition, understanding the terminology used by universities and colleges will play an integral role in planning your future.

University and College Programs

Undergraduate university programs generally lead to a three-year general bachelor degree or a four-year honours bachelor degree. These degree designations begin with a "B" followed by the area of specialization; for example, a B.Sc. (Hons.) indicates an Honours Bachelor of Science degree. These degrees can lead to employment or to further education in Masters or Doctorate post-graduate programs.

College programs typically fall into three categories: one-year certificates, two-year diplomas, and three-year advanced diplomas. Certificates and diplomas can lead directly to employment opportunities or to graduate certificate programs. In some programs, there are "transfer agreements" with universities, which allow college graduates to enter university programs with advanced standing toward a university degree.

Pathways in Biology

The Career Pathways graphic organizer illustrates possible pathways to follow after high school. Certain pathways lead to careers via university while others may lead to careers via college. Look at **Figure 1** below. The pathways of two students are highlighted, both requiring students to complete the Grades 11 and 12 University Biology courses (along with other prerequisites) and initially enter an undergraduate university program.

Student A wishes to become a veterinarian. Since veterinary medicine is a second-entry program, student A must first obtain the necessary university-level prerequisites for veterinary medicine in an undergraduate science program. Student A can then continue to a Doctor of Veterinary Medicine program and ultimately become a veterinarian.

Student B wishes to become an anthropologist. Student B must first obtain a Bachelor of Arts degree and then can seek employment as an anthropologist.

Student C could become a horticulturist by completing a college certificate program, then seeking an apprenticeship or employment as a horticulturist.

Planning for Your Future

Planning ahead for your educational and career paths will provide a rewarding future. You should consult your guidance counsellors for specific advice on career planning and which courses you should take in high school. Take the time to research university and college websites for specific program information as these sites will provide the prerequisite information and, most often, career planning advice. While it may seem overwhelming at times, utilizing as many resources as possible will help alleviate some of the stress in planning your future.

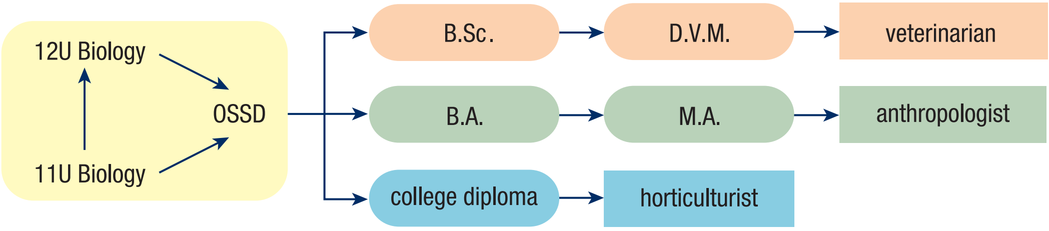


Figure 1 This graphic organizer shows pathways to several careers in biology. The pathway for student A, who wishes to become a veterinarian, is highlighted in orange. The pathway for student B, who wishes to become an anthropologist, is highlighted in green. The pathway for student C, who wishes to become a horticulturist, is highlighted in blue.

APPENDIX B REFERENCE

Throughout *Nelson Biology 12* and in this reference section, we have attempted to be consistent in the presentation and usage of units. As far as possible, the text uses the International System of Units (SI). However, some other units have been included because of their practical importance, wide usage, or use in specialized fields.

Nelson Biology 12 has followed the most recent *Canadian Metric Practice Guide* (CAN/CSA-Z234.1-00), published in 2000 and updated in 2003 by the Canadian Standards Association.

Table 1 SI Base Units

Quantity	Symbol	Unit name	Symbol
amount of substance	n	mole	mol
length	L, l, h, d, w	metre	m
mass	m	kilogram	kg
time	t	second	s

Table 2 Some SI-Derived Units

Quantity	Symbol	Unit	Unit symbol	SI base unit
area	A	square metre	m^2	m^2
Celsius temperature	t	Celsius	°C	K
density	ρ, D	kilogram per cubic metre	kg/m^3	kg/m^3
displacement	$\Delta\vec{\delta}$	metre	m	m
energy	$E, E_{k,} E_p$	joule	J	$kg{\cdot}m^2/s^2$
force	F	newton	N	$kg{\cdot}m/s^2$
frequency	f	hertz	Hz	s^{-1}
heat	Q	joule	J	$kg{\cdot}m^2/s^2$
pressure	p	newton per square metre	N/m^2	$kg/m{\cdot}s^2$
volume	V	cubic metre	m^3	m^3
weight	W, w	newton	N	N, $kg{\cdot}m/s^2$
work	W	joule	J	$kg{\cdot}m^2/s^2$

LEARNING TIP

SI Prefixes

Sometimes it is difficult to remember the metric prefixes. A mnemonic is a saying that helps you remember something. "King Henry Doesn't Mind Drinking Chocolate Milk" is a mnemonic for kilo, hecto, deca, metre, deci, centi, and milli. Another helpful hint is that mega (M) represents a million ($\times 10^6$) and tera (T) represents a trillion ($\times 10^{12}$). The first letters of the prefix and of what it represents are the same. Keep this in mind as you read Table 3.

Table 3 Numerical Prefixes

Powers and Subpowers of Ten		
Prefix	**Power**	**Symbol**
deca	10^1	da
hecto	10^2	h
kilo	10^3	k
mega	10^6	M
giga	10^9	G
tera	10^{12}	T
peta	10^{15}	P
exa	10^{18}	E
deci	10^{-1}	d
centi	10^{-2}	c
milli	10^{-3}	m
micro	10^{-6}	μ
nano	10^{-9}	n
pico	10^{-12}	p
femto	10^{-15}	f
atto	10^{-18}	a

Some Examples of Prefix Use

2000 metres = 2×10^3 metres = 2 **kilo**metres or 2 km
0.27 metres = 27×10^{-2} metres = 27 **centi**metres or 27 cm
3 000 000 000 hertz = 3×10^9 hertz = 3 **giga**hertz or 3 gHz

Table 4 Greek and Latin Prefixes

Prefix	Meaning	Prefix	Meaning	Prefix	Meaning
a-	not, without	cyt-, cyto-	cell	intro-	inward
ab-	away from	dendr-, dendri-, dendro-	tree	iso-	equal
abd-	led away	dent-, denti-	tooth	lact-, lacti-, lacto-	milk
acro-	end, tip	derm-	skin	leuc-, leuco-	white
adip-	fat	di-	two	lip-, lipo-	fat
aer-, aero-	air	dors-	back	lymph-, lympho-	clear water
agg-	to clump	ec-, ecto-	outside	lys-, lyso-	break up
agro-	land	em-	inside	macro-	large
alb-	white	en-	in	mamm-	breast
allo-	other	end-, endo-	within	meg-, mega-	great
ameb-	change	epi-	at, on, over	melan-	black
amphi-	around, both	equi-	equal	meningo-	membrane
amyl-	starch	erythro-	red	mes-, meso-	middle
an-	without	ex-, exo-	away, out	meta-	after, transition
ana-	up	flag-	whip	micr-, micro-	small
andro-	man	gamet-, gamo-	marriage, united	mono-	one
ant-, anti-	opposite	gastr-, gastro-	stomach	morpho-	form, shape
anth-	flower	geo-	earth	muc-, muco-	slime
archae-, archaeo-	ancient	glyc-	sweet	multi-	many
archi-	primitive	halo-	salt	myo-	muscle
astr-, astro-	star	haplo-	single	nas-	nose
aut-, auto-	self	hem-, hema-, hemato-	blood	necro-	corpse
baro-	weight (pressure)	hemi-	half	neo-	new
bi-	twice	hepat-, hepa-	liver	neur-, neuro-	nerve
bio-	life	hetero-	different	noct-	night
blast-, blasto-	sprout (budding)	histo-	web	odont-, odonto-	tooth
carcin-	cancer	holo-	whole	oligo-	few
cardio-, cardia-	heart	homeo-	same	oo-	egg
chlor-, chloro-	green	hydro-	water	orni-	bird
chrom-, chromo-	colour	hyper-	above	oss-, osseo-, osteo-	bone
co-	with	hypo-	below	ovi-	egg
cosmo-	order, world	infra-	under	pale-, paleo-	ancient
cut-	skin	inter-	between	patho-	disease
cyan-	blue	intra-	inside of, within	peri-	around

Table 4 Greek and Latin Prefixes (continued)

Prefix	Meaning	Prefix	Meaning	Prefix	Meaning
petro-	rock	sacchar-, saccharo-	sugar	trich-	hair
phag-, phago-	eat	sapr-, sapro-	rotten	ultra-	beyond
pharmaco-	drug	soma-	body	uro-	tail, urine
phono-	sound	spermato-	seed	vas-, vaso-	vessel
photo-	light	sporo-	seed	vita-	life
pneum-	air	squam-	scale	vitro-	glass
pod-	foot	sub-	beneath	vivi-	alive
poly-	many	super-, supra-	above	xanth-, xantho-	yellow
pseud-, pseudo-	false	sym-, syn-	with, together	xer-, xero-	dry
pyr-, pyro-	fire	telo-	end	xyl-	wood
radio-	ray	therm-, thermo-	temperature, heat	zoo-	animal
ren-	kidney	tox-	poison	zygo-	yoke
rhizo-	root	trans-	across		

Table 5 Greek and Latin Suffixes

Suffix	Meaning	Suffix	Meaning	Suffix	Meaning
-aceous	like	-lysis	loosening	-phyll	leaf
-blast	budding	-lyt	dissolvable	-phyte	plant
-cide	kill	-mere	share	-pod	foot
-crin	secrete	-metry	measure	-sis	a condition
-cut	skin	-mnesia	memory	-some	body
-cyte	cell	-oid	like	-stas, -stasis	halt
-emia	blood	-ol	alcohol	-stat	to stand, stabilize
-gen	born, agent	-ole	oil	-tone, -tonic	strength
-genesis	formation	-oma	tumour	-troph	nourishment
-graph, -graphy	to write	-osis	a condition	-ty	state of
-gynous	woman	-pathy	suffering	-vorous	eat
-itis	inflammation	-ped	foot	-yl	wood
-logy	the study of	-phage	eat	-zyme	ferment

Table 6 Selected Letters of the Greek Alphabet

A	α	alpha
B	β	beta
Δ	δ	delta
Θ	θ	theta
Λ	λ	lambda
M	μ	mu
Π	π	pi

Table 7 Data for Some Radioisotopes

Atomic number (*Z*)	Name	Symbol	Atomic mass (u)	Decay type	Half-life
6	carbon-14	$^{14}_{6}\mathrm{C}$	14.003 242	β^-	5730 years
8	oxygen-15	$^{15}_{8}\mathrm{O}$	15.003 065	β^+	122.24 s
15	phosphorus-32	$^{32}_{15}\mathrm{P}$	31.973 908	β^-	14.262 days
19	potassium-40	$^{40}_{19}\mathrm{K}$	39.96 400	β^-, β^+	1.28×10^9 years
53	iodine-131	$^{131}_{53}\mathrm{I}$	130.906 111	β^-, γ	8.04 days
86	radon-222	$^{222}_{86}\mathrm{Rn}$	222.017 571	α, γ	3.8235 s

Table 8 Messenger Ribonucleic Acid (mRNA) Codons and Their Corresponding Amino Acids

	Second Base				
First Base	**U**	**C**	**A**	**G**	**Third Base**
U	UUU phenylalanine	UCU serine	UAU tyrosine	UGU cysteine	**U**
	UUC phenylalanine	UCC serine	UAC tyrosine	UGC cysteine	**C**
	UUA leucine	UCA serine	UAA STOP**	UGA STOP**	**A**
	UUG leucine	UCG serine	UAG STOP**	UGG tryptophan	**G**
C	CUU leucine	CCU proline	CAU histidine	CGU arginine	**U**
	CUC leucine	CCC proline	CAC histidine	CGC arginine	**C**
	CUA leucine	CCA proline	CAA glutamine	CGA arginine	**A**
	CUG leucine	CCG proline	CAG glutamine	CGG arginine	**G**
A	AUU isoleucine	ACU threonine	AAU asparagine	AGU serine	**U**
	AUC isoleucine	ACC threonine	AAC asparagine	AGC serine	**C**
	AUA isoleucine	ACA threonine	AAA lysine	AGA arginine	**A**
	AUG methionine*	ACG threonine	AAG lysine	AGG arginine	**G**
G	GUU valine	GCU alanine	GAU aspartate	GGU glycine	**U**
	GUC valine	GCC alanine	GAC aspartate	GGC glycine	**C**
	GUA valine	GCA alanine	GAA glutamate	GGA glycine	**A**
	GUG valine	GCG alanine	GAG glutamate	GGG glycine	**G**

* AUG is an initiator codon and also codes for the amino acid methionine.
** UAA, UAG, and UGA are terminator codons.

Table 9 Glands in the Human Endocrine System

Endocrine gland/ hormone source	Hormone produced	Target tissue	Function
hypothalamus	releasing and inhibiting hormones	anterior pituitary	regulate secretion of anterior pituitary hormones, such as growth hormone–releasing hormone (GHRH) and growth hormone–inhibiting hormone (somatostatin)
anterior pituitary	prolactin (PRL)	mammary glands	stimulates breast development and milk secretion
	growth hormone (GH)	bone and soft tissue	stimulates growth of bones and soft tissues; helps to control metabolism of glucose and other fuel molecules
	thyroid-stimulating hormone (TSH)	thyroid gland	stimulates secretion of thyroid hormones and growth of thyroid gland
	adrenocorticotropic hormone (ACTH)	adrenal cortex	stimulates secretion of glucocorticoids by adrenal cortex
	follicle-stimulating hormone (FSH)	ovaries in females and testes in males	stimulates growth of eggs and development and secretion of sex hormones in females; stimulates sperm production in males
	luteinizing hormone (LH)	ovaries in females and testes in males	regulates ovulation in females; regulates secretion of sex hormones in males
	melanocyte-stimulating hormone (MSH)	melanocytes in skin of some vertebrates	promotes darkening of the skin
	endorphins	pain pathways of the PNS	inhibit perception of pain
posterior pituitary	antidiuretic hormone (ADH)	kidneys	increases blood volume and pressure by increasing water reabsorption in kidneys
	oxytocin	uterus and mammary glands	promotes uterine contractions; stimulates milk ejection from breasts
thyroid	calcitonin	bone	lowers calcium concentration in blood
	thyroxine and triiodothyronine	most cells	increase metabolic rate; essential for normal body growth
parathyroid	parathyroid hormone (PTH)	bone, kidneys, and intestines	raises calcium concentration in blood; stimulates vitamin D activation
adrenal medulla	epinephrine and norepinephrine	receptor sites throughout body	contribute to body's responses to stress
adrenal cortex	aldosterone (mineralocorticoid)	kidney tubules	helps to control body's salt–water balance by increasing Na^+ reabsorption and K^+ excretion in kidneys
	cortisol (glucocorticoid)	most body cells, particularly muscle, liver, and adipose cells	increases blood glucose by promoting breakdown of proteins and fats
pineal gland	melatonin	brain, anterior pituitary gland, reproductive organs, immune system, and possibly other tissues	helps to synchronize body's biological clock with day length; may inhibit gonadotropins and initiation of puberty
ovaries	estrogens, such as estradiol	many body cells and tissues	stimulate maturation of sex organs at puberty and the development of secondary sexual characteristics in females
testes	androgens, such as testosterone	many body cells	stimulate puberty and the development of secondary sexual characteristics in males

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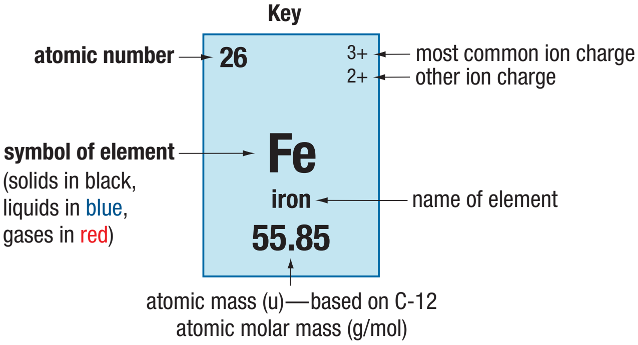

	1	2	3	4	5	6	7	8	9
1	1 1+ 1− **H** hydrogen 1.01								
2	3 1+ **Li** lithium 6.94	4 2+ **Be** beryllium 9.01							
3	11 1+ **Na** sodium 22.99	12 2+ **Mg** magnesium 24.31							
4	19 1+ **K** potassium 39.10	20 2+ **Ca** calcium 40.08	21 3+ **Sc** scandium 44.96	22 4+ 3+ **Ti** titanium 47.87	23 5+ 4+ **V** vanadium 50.94	24 3+ 2+ **Cr** chromium 52.00	25 2+ 4+ **Mn** manganese 54.94	26 3+ 2+ **Fe** iron 55.85	27 2+ 3+ **Co** cobalt 58.93
5	37 1+ **Rb** rubidium 85.47	38 2+ **Sr** strontium 87.62	39 3+ **Y** yttrium 88.91	40 4+ **Zr** zirconium 91.22	41 5+ 3+ **Nb** niobium 92.91	42 6+ **Mo** molybdenum 95.96	43 7+ **Tc** technetium (98)	44 3+ 4+ **Ru** ruthenium 101.07	45 3+ **Rh** rhodium 102.91
6	55 1+ **Cs** cesium 132.91	56 2+ **Ba** barium 137.33	57 3+ 2+ **La** lanthanum 138.91	72 4+ **Hf** hafnium 178.49	73 5+ **Ta** tantalum 180.95	74 6+ **W** tungsten 183.84	75 7+ **Re** rhenium 186.21	76 4+ **Os** osmium 190.23	77 4+ **Ir** iridium 192.22
7	87 1+ **Fr** francium (223)	88 2+ **Ra** radium (226)	89 3+ 2+ **Ac** actinium (227)	104 **Rf** rutherfordium (261)	105 **Db** dubnium (262)	106 **Sg** seaborgium (266)	107 **Bh** bohrium (264)	108 **Hs** hassium (277)	109 **Mt** meitnerium (268)
	Alkali metals	**Alkaline earth metals**							

6	58 3+ **Ce** cerium 140.12	59 3+ **Pr** praseodymium 140.91	60 3+ **Nd** neodymium 144.24	61 3+ **Pm** promethium (145)	62 3+ 2+ **Sm** samarium 150.36
7	90 4+ **Th** thorium 232.04	91 5+ 4+ **Pa** protactinium 231.04	92 6+ 4+ **U** uranium 238.03	93 5+ **Np** neptunium (237)	94 4+ 6+ **Pu** plutonium (244)

- 🟦 metals
- 🟩 metalloids
- 🟥 non-metals
- 🟨 hydrogen

Periodic Table of the Elements

Measured values are subject to change as experimental techniques improve.

Atomic molar mass values in this table are based on IUPAC website values (2011).

10	11	12	13	14	15	16	17	18	
								2 — **He** helium 4.00	1
			5 — **B** boron 10.81	6 — **C** carbon 12.01	7 3– **N** nitrogen 14.01	8 2– **O** oxygen 16.00	9 1– **F** fluorine 19.00	10 — **Ne** neon 20.18	2
			13 3+ **Al** aluminum 26.98	14 — **Si** silicon 28.09	15 3– **P** phosphorus 30.97	16 2– **S** sulfur 32.07	17 1– **Cl** chlorine 35.45	18 — **Ar** argon 39.95	3
28 2+ 3+ **Ni** nickel 58.69	29 2+ 1+ **Cu** copper 63.55	30 2+ **Zn** zinc 65.38	31 3+ **Ga** gallium 69.72	32 4+ **Ge** germanium 72.64	33 3– **As** arsenic 74.92	34 2– **Se** selenium 78.96	35 1– **Br** bromine 79.90	36 — **Kr** krypton 83.80	4
46 2+ 3+ **Pd** palladium 106.42	47 1+ **Ag** silver 107.87	48 2+ **Cd** cadmium 112.41	49 3+ **In** indium 114.82	50 4+ 2+ **Sn** tin 118.71	51 3+ 5+ **Sb** antimony 121.76	52 2– **Te** tellurium 127.60	53 1– **I** iodine 126.90	54 — **Xe** xenon 131.29	5
78 4+ 2+ **Pt** platinum 195.08	79 3+ 1+ **Au** gold 196.97	80 2+ 1+ **Hg** mercury 200.59	81 1+ 3+ **Tl** thallium 204.38	82 2+ 4+ **Pb** lead 207.2	83 3+ 5+ **Bi** bismuth 208.98	84 2+ 4+ **Po** polonium (209)	85 1– **At** astatine (210)	86 — **Rn** radon (222)	6
110 **Ds** darmstadtium (281)	111 **Rg** roentgenium (272)	112 **Cn** copernicium (285)	113 **Uut** ununtrium (284)	114 **Uuq** ununquadium (289)	115 **Uup** ununpentium (288)	116 **Uuh** ununhexium (291)	117 **Uus** ununseptium (294)	118 **Uuo** ununoctium (294)	7
							Halogens	Noble gases	

63 3+ 2+ **Eu** europium 151.96	64 3+ **Gd** gadolinium 157.25	65 3+ **Tb** terbium 158.93	66 3+ **Dy** dysprosium 162.50	67 3+ **Ho** holmium 164.93	68 3+ **Er** erbium 167.26	69 3+ **Tm** thulium 168.93	70 3+ 2+ **Yb** ytterbium 173.05	71 2+ **Lu** lutetium 174.97	6
95 3+ 4+ **Am** americium (243)	96 3+ **Cm** curium (247)	97 3+ 4+ **Bk** berkelium (247)	98 3+ **Cf** californium (251)	99 3+ **Es** einsteinium (252)	100 3+ **Fm** fermium (257)	101 2+ 3+ **Md** mendelevium (258)	102 2+ 3+ **No** nobelium (259)	103 3+ **Lr** lawrencium (262)	7

APPENDIX C ANSWERS

These pages include numerical and short answers to chapter section questions and Chapter Self-Quiz, Chapter Review, Unit Self-Quiz, and Unit Review questions.

Unit 1

Are You Ready? pp. 4–5

2. covalent bonds
5. (a) (i) 1
(ii) 2
(iii) 4
(iv) 3
6. (a) ii
(b) iii
(c) iv
(d) i
7. (a) acid
(b) base
(c) salt and water
11. (a) A: Golgi bodies; B: plasma membrane; C: mitochondrion; D: vacuole; E: cytosol; F: ribosome; G: nucleus; H: endoplasmic reticulum
(b) animal cell
13. (a) iii
(b) iv
(c) ii
(d) i
17. (a) 5 atoms; 16.0 g/mol
(b) 24 atoms; 180 g/mol
(c) 14 atoms; 92.1 g/mol
18. (a) $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$
(b) $2CH_2O_2 \rightarrow C_2H_2O_3 + H_2O$
(c) $C_6H_{12}O_6 \rightarrow 2C_2H_6O + 2CO_2$
19. (a) ii
(b) i

1.1 Questions, p. 18

1. (a) carbon-13, carbon-15
2. (a) ^1H (protium or hydrogen), ^2H (deuterium), ^3H (tritium)
3. (a) $1s^2$, $2s^2$, and $2p^4$
(b) oxygen
9. nitrogen

1.2 Questions, p. 24

4. no

1.3 Questions, p. 28

6. (a) lose H^+
(b) gain H^+
(c) lose H^+
9. hydrolysis
12. (a) Figure 7: amine group, carboxyl group; Figure 8: phosphate group, carbonyl group, hydroxyl group

1.4 Questions, p. 38

1. (b) figures (iii) and (iv)

1.5 Questions, p. 47

1. amine group, carboxylic acid, R group

1.7 Questions, p. 57

5. (a) increase
(b) proportional to enzyme concentration
(c) increase to optimal temperature
(d) increase to optimal pH

Chapter 1 Self-Quiz, p. 63

1. c
2. c
3. c
4. d
5. d
6. c
7. c
8. a
9. b
10. d
11. b
12. T
13. F
14. T
15. F
16. T
17. T
18. F
19. F

Chapter 1 Review, pp. 64–69

1. c
2. d
3. b
4. d
5. d
6. b
7. a
8. d
9. a
10. b
11. a
12. b
13. a
14. b
15. a
16. a
17. c
18. c
19. c
20. a
21. F
22. F
23. T
24. F
25. F
26. T
27. F
28. F
29. T
30. F
31. F
32. F
33. F
34. T
35. T
36. T
37. F

38. (a) ii
(b) iv
(c) i
(d) iii
39. (a) iv
(b) iii
(c) ii
(d) i
40. (a) ii
(b) iii
(c) i
41. carbon; hydrogen; oxygen; nitrogen
49. carbon; hydrogen; oxygen
51. carbohydrates; lipids; proteins; nucleic acids
58. (a) uracil; thymine; cytosine; adenine; guanine
72. (a) monosaccharide
(b) $C_5H_{10}O_5$
(c) carbohydrate
88. (b) OH and H
91. (a) 38 °C
(b) 8.5
(c) 4

2.1 Questions, p. 80

7. (a) Golgi body

2.2 Questions, p. 86

5. (c) temperature, lipid composition
(d) e.g., cholesterol
7. non-polar
13. no

2.4 Questions, p. 97

1. (b) no
8. (a) endocytosis

Chapter 2 Self-Quiz, p. 101

1. b
2. a
3. a
4. a
5. b
6. b
7. b
8. d
9. a
10. T
11. F
12. F
13. T
14. T
15. T
16. F
17. T
18. T
19. F

Chapter 2 Review, pp. 102–107

1. b
2. d
3. b
4. c
5. c
6. d
7. b
8. c
9. b
10. b
11. b
12. a
13. d
14. c
15. c
16. F
17. F
18. T
19. T
20. F
21. F
22. T
23. F
24. F
25. F
26. F
27. T
28. T
29. T
30. F
31. F

32. (a) viii
(b) iii
(c) vi
(d) iv
(e) i
(f) vii
(g) ii
(h) v
33. (a) iii
(b) iv
(c) ii
(d) i
40. (a) nucleus; ER; Golgi body; vesicles; mitochondrion; plastids; lysosome; peroxisome; vacuole
(b) ER; Golgi body
43. (a) chloroplast
(b) photosynthetic eukaryotes
(c) membrane
48. transport; enzymatic activity; triggering signals; attachment and recognition
49. A: integral proteins
B: peripheral proteins
C: polar end
D: non-polar end
E: phospholipid molecule
F: cytosol
G: cholesterol
51. cancer research; cell and bone repair; gene therapy; drug delivery
54. (a) passive diffusion; facilitated diffusion; endocytosis
(b) active transport; exocytosis
59. (b) tubers
66. (a) no
67. (b) (i) no
(ii) rapidly
(iii) rapidly
(iv) very rapidly
69. (a) ATP
(b) about 25 %

Unit 1 Self-Quiz, pp. 110–111

1. b
2. d
3. c
4. d
5. d
6. c
7. b
8. a
9. d
10. b
11. b
12. d
13. a
14. c
15. c
16. a
17. a
18. c
19. b
20. b
21. T
22. F
23. T
24. F
25. T
26. T
27. F
28. T
29. T
30. F
31. F
32. F
33. T
34. F
35. F
36. F
37. T
38. F
39. F
40. T
41. F
42. T
43. F

Unit 1 Review, pp. 112–119

1. a
2. c
3. c
4. d
5. a
6. b
7. d
8. b
9. c
10. b
11. a
12. c
13. d
14. b
15. d
16. a
17. c
18. c
19. b
20. d
21. c
22. d
23. F
24. T
25. T
26. F
27. T
28. T
29. F
30. T
31. F
32. F
33. F
34. T
35. F
36. F
37. T
38. F
39. T
40. F
41. T

42. (a) v
(b) vi
(c) iii
(d) i
(e) iv
(f) ii
43. (a) iii
(b) vi
(c) v
(d) iv
(e) ii
(f) i
45. two
56. RNA; proteins
59. (a) cystic fibrosis transmembrane conductance regulator (CFTR)
68. (a) unsaturated fatty acid chains
71. CTAATTG
74. (a) 37 °C
(b) 55 °C
76. (a) rough ER
(c) mitochondrion
(d) ribosome
77. (a) mitochondrion
88. (b) (i) secondary
(ii) primary
(ii) tertiary
(iv) secondary
(v) primary
89. no

97. no
98. (a) active process
    (b) sodium-potassium pump
99. (b) (i) exocytosis
    (ii) endocytosis
    (iii) exocytosis

Unit 2

Are You Ready? pp. 122–123

4. (b) bond breaking
7. outside to inside cell
10. (a) ii
    (b) i
    (c) iv
    (d) iii
11. (a) iii
    (b) ii
    (c) v
    (d) i
    (e) iv
12. (a) both
    (b) both
    (c) both
    (d) consumer
    (e) both
    (f) consumer
18. (a) $6\ CO_2 + 12\ H_2O \rightarrow C_6H_{12}O_6 + 6\ H_2O + 6\ O_2$
    (b) $C_2H_5OH + 3\ O_2 \rightarrow 2\ CO_2 + 3\ H_2O$
19. (b) glucose: 7, ethanol: 5
    (c) glucose: 5, ethanol: 1
    (d) glucose: 5, ethanol: 1
    (e) glucose: 7, ethanol: 1
20. 1×10^3 J
23. (a) (i) 74 g/mol
    (ii) 45 g/mol
    (iii) 142 g/mol
    (c) (i) polar
    (ii) polar
    (iii) non-polar
    (d) (i) acidic
    (ii) basic
    (iii) neutral
24. (a) exothermic
    (b) exothermic
    (c) endothermic

3.1 Questions, p. 140

3. (a) 47 kJ/g of ethane; exothermic
    (c) hydrocarbons
4. exothermic
6. exergonic
8. (a) spontaneous
    (b) non-spontaneous
    (c) spontaneous
    (d) non-spontaneous
10. (a) spontaneous
    (b) non-spontaneous
    (c) spontaneous
    (d) non-spontaneous

3.2 Questions, p. 145

7. group 1
11. (a) ii and iii
    (b) i and iii; ii and iv; iii and iv

3.3 Questions, p. 150

5. Reaction B

3.4 Questions, p. 155

2. (a) $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$
    (b) oxygen
    (c) glucose
8. (a) nitrogen
    (b) carbon
    (c) no

Chapter 3 Self-Quiz, p. 159

1. b
2. c
3. d
4. d
5. c
6. d
7. d
8. b
9. T
10. F
11. F
12. F
13. F
14. F
15. T
16. T
17. F
18. T
19. F
20. F

Chapter 3 Review, pp. 160–165

1. c
2. a
3. b
4. d
5. d
6. b
7. a
8. a
9. d
10. b
11. F
12. T
13. T
14. T
15. F
16. F
17. T
18. F
19. T

20. (a) iv
    (b) iii
    (c) ii
    (d) i
21. (a) iv
    (b) i
    (c) ii
    (d) iii
22. (a) iv
    (b) i
    (c) iii
    (d) ii
23. (a) O–H
    (b) C–O
24. yes
30. (a) A: reactants
    B: transition state
    C: products
    D: activation energy
    E: energy released by reaction
    (b) exothermic
53. (b) catabolic
56. (a) 1409 kJ/mol of ethane
    (b) 14 kJ/g of fructose
58. spontaneous
59. (a) 8.54 kJ/g
    (b) 15.1 kJ/g
60. (a) exergonic
    (b) yes
73. crop Y

4.1 Questions, p. 171

1. (a) ATP
    (b) provides energy
5. (a) $C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$
6. four stages
7. (a) glycolysis
    (b) pyruvate, oxygen

4.2 Questions, p. 182

3. NADH, $FADH_2$, ADP, and P_i
5. (a) most free energy
    (b) release energy
7. (a) glucose + 2 ADP + 2 P_i + 2 $NAD^+ \rightarrow$ 2 pyruvate + 2 ATP + 2 NADH + 2 H^+
    (b) 2 pyruvate + 2 NAD^+ + 2 CoA $\rightarrow$ 2 acetyl-CoA + 2 NADH + 2 H^+ + 2 CO_2
    (c) acetyl-CoA + 3 NAD^+ + FAD + ADP + P_i + 2 $H_2O \rightarrow$ 2 CO_2 + 3 NADH + 3 H^+ + $FADH_2$ + ATP + CoA
8. oxygen
12. (a) water
    (b) one

4.3 Questions, p. 189

1. 3 ATP for every NADH; 2 ATP for every $FADH_2$
2. (a) 38 ATP total
7. yes

4.4 Questions, p. 194

5. no

Chapter 4 Self-Quiz, pp. 203

1. c
2. c
3. b
4. d
5. c
6. a
7. d
8. d
9. d
10. F
11. F
12. F
13. F
14. F
15. F
16. T
17. F
18. F
19. F
20. T
21. F

Chapter 4 Review, pp. 204–209

1. c
2. a
3. c
4. b
5. d
6. d
7. b
8. c
9. d
10. d
11. F
12. F
13. T
14. F
15. F
16. T
17. T
18. F

19. (a) ii
    (b) iii
    (c) v
    (d) i
    (e) iv
24. carbon dioxide and water
25. NADH, $FADH_2$, and H^+
26. lactate fermentation
40. (a) NADH and $FADH_2$
41. 38 ATP
44. no
53. (a) pyruvate, NADH, and H^+
    (b) NADH and H^+ to pyruvate
68. (a) alcohol fermentation: pyruvate + NADH + $H^+ \rightarrow$ ethanol + NAD^+ + CO_2
    (b) lactate fermentation: pyruvate + NADH + $H^+ \rightarrow$ lactate + NAD^+
    (c) pyruvate oxidation: pyruvate + NAD^+ + CoA $\rightarrow$ acetyl-CoA + NADH + H^+ + CO_2
74. (a) 1.0×10^{20} molecules of ATP
    (b) 2.6×10^{18} glucose molecules
    (c) 7.9×10^{-4} g of glucose

5.1 Questions, p. 219

4. (a) less
    (b) green light source

5.2 Questions, p. 228

9. cyclic electron transport; photosystem I

5.4 Questions, p. 234

5. (a) C_4 plant
    (b) CAM plant
    (c) C_3 plant
    (d) C_4 plant
9. CAM

5.6 Questions, p. 240

1. chloroplasts; no
2. mitochondria; yes
3. (c) glucose; water
4. yes; no

Chapter 5 Self-Quiz, p. 245

1. c
2. a
3. b
4. d
5. a
6. c
7. d
8. b
9. c
10. d
11. a
12. F
13. T
14. T
15. F
16. F
17. T
18. F
19. F

Chapter 5 Review, pp. 246–251

1. a
2. b
3. b
4. d
5. d
6. b
7. b
8. b
9. b
10. a
11. T
12. F
13. F
14. F
15. T
16. F
17. F
18. T
19. F
20. F

21. (a) v
    (b) iv
    (c) i
    (d) iii
    (e) ii
22. (a) ii
    (b) iv
    (c) v
    (d) iii
    (e) i
26. no
41. red light
44. no
45. photons
50. southern Ontario
62. (b) violet–blue; green–yellow
    (d) no light absorbed
    (e) chlorophyll *a* and chlorophyll *b*
68. (a) negative effect
    (b) positive effect
    (c) negative effect
80. yes

Unit 2 Self-Quiz, pp. 254–255

1. a
2. d
3. d
4. d
5. b
6. a
7. a
8. d
9. c
10. a
11. c
12. c
13. d
14. d
15. d
16. a
17. a
18. c
19. a
20. T
21. F
22. T
23. F
24. F
25. F
26. T
27. F
28. F
29. F
30. T
31. T
32. F
33. T
34. T
35. F
36. T
37. F
38. F
39. T
40. T
41. F

Unit 2 Review, pp. 256–263

1. b
2. d
3. a
4. c
5. c
6. b
7. c
8. a
9. d
10. d
11. d
12. d
13. F
14. F
15. F
16. F
17. F
18. F
19. F
20. F
21. F
22. T
23. F
24. F

25. (a) v
    (b) iii
    (c) i
    (d) ii
    (e) iv
26. ATP + H_2O → ADP + P_i
35. no
37. P680, P680*, $P680^+$
39. (a) endothermic
41. (a) catabolic: pathway (b); anabolic: pathway (a)
    (b) pathway (a)
42. (a) exergonic
52. fermentation
54. high light plant
60. (a) 32.4 %
    (b) thermal energy
62. (b) Graph Y: exothermic; Graph Z: endothermic
63. (b) yes
66. lipid (a)
69. (a) 4.39 kg
    (b) no
76. fats
78. (a) glucose
85. egg
93. no

Unit 3

Are You Ready? pp. 266–267

3. (a) nucleus
   (b) nucleoid
4. no
5. S phase
11. (b) no
12. TATCCGTAGGT
15. 1.2×10^{-6}
16. (a) 19.8 % DNA; 6.4 % RNA; 63.4 % protein
    (b) 3:1:10
    (c) 1.98 g
    (d) 70 % yield
    (e) 40 %
19. (b) no detergent
20. Figure 2
21. (c) independent: age; dependent: errors

6.1 Questions, p. 272

2. 0.99 m
3. gene; chromosome; genome; nucleus
6. yes

6.2 Questions, p. 279

2. 18 % G; 18 % C; 32 % T
4. CACTGATTGTCACCGGTA

6.4 Questions, p. 290

2. helicase; topoisomerase; RNA primase; DNA polymerase III; DNA polymerase I; DNA ligase
5. yes

6.5 Questions, p. 294

1. histone; nucleosome; solenoid; chromosome
2. 333

Chapter 6 Self-Quiz, p. 303

1. d
2. d
3. b
4. c
5. a
6. c
7. b
8. d
9. c
10. a
11. b
12. F
13. F
14. T
15. T
16. F
17. T
18. F
19. F

Chapter 6 Review, pp. 304–309

1. d
2. d
3. b
4. c
5. b
6. d
7. b
8. a
9. b
10. d
11. c
12. d
13. a
14. F
15. F
16. T
17. T
18. F
19. F
20. F
21. F
22. F
23. T

24. (a) ii
    (b) iii
    (c) i
    (d) iv
25. (a) ii
    (b) iv
    (c) iii
    (d) i
26. (a) i
    (b) ii
    (c) iv
    (d) iii
27. A: nitrogenous bases; B: base pairs; C: backbone; D: double helix
29. 33 % A; 14 % T; 32 % C; 21 % G
37. (b) nucleotides
40. (a) B
    (b) A; C; D
46. telomeres
48. 680
49. 24 % G; 26 % A; 26 % T
50. (a) 1 m
    (b) 3×10^8 coils
51. (a) 2.2×10^8
    (b) 4.4×10^8
59. (a) 4.6×10^3 s
    (b) 3×10^6 s
61. (a) RNA primers; RNA primase; DNA ligase
    (b) no

7.1 Questions, p. 318

4. rRNA, tRNA, mRNA
6. UUAACGUAUAUGCCCUUUAUGCUGGCC
7. 256; 1024
8. (a) Met Leu Ala His Arg Gly Phe

7.2 Questions, p. 324

1. initiation; elongation; termination
2. 5′-GUUUAACCGAAUAAUGGCCUAC-3′

7.5 Questions, p. 345

2. (a) insertion
   (b) nonsense
   (c) frameshift
5. nonsense mutation; stop codon

Chapter 7 Self-Quiz, p. 357

1. b
2. b
3. d
4. c
5. d
6. b
7. d
8. a
9. d
10. d
11. F
12. T
13. T
14. F
15. F
16. T
17. T
18. F
19. T
20. T

Chapter 7 Review, pp. 358–363

1. d
2. a
3. d
4. a
5. d
6. b
7. a
8. c
9. b
10. b
11. a
12. c
13. c
14. c
15. c
16. b
17. T
18. F
19. F
20. F
21. F
22. F
23. T
24. T
25. F
26. T
27. F
28. F
29. T
30. F
31. F
32. T

33. (a) iv
    (b) iii
    (c) i
    (d) vi
    (e) v
    (f) ii
34. (a) iii
    (b) iv
    (c) vi
    (d) ii
    (e) i
    (f) v
35. valine, aspartic acid, phenylalanine, arginine
47. RNA
52. 70 kbp is eukaryote; 20 kbp is prokaryote
67. 60 °C strand
70. 20 tRNA
71. 3 stop codons
73. silent mutation
76. (b) 59:2
82. (a) sequence B
    (b) sequence A: 3; sequence B: 2; TATA box
    (c) sequence A: 3; sequence B: 2
83. (a) frameshift
    (b) silent
    (c) frameshift

8.1 Questions, p. 375

2. HindIII
6. 117 cuts
8. (a) (i) 6660; 1236
       (ii) 1399; 6497
       (iii) 429; 1071; 6396
       (iv) 372; 429; 1071; 1236; 4788
       (v) 372; 429; 1071; 1056; 1236; 1399; 2333
   (b) BamHI

8.2 Questions, p. 385

7. (a) 200 bp
   (b) 1800 bp

Chapter 8 Self-Quiz, p. 403

1. b
2. d
3. a
4. b
5. d
6. d
7. d
8. d
9. b
10. c
11. T
12. T
13. F
14. T
15. F
16. T
17. T
18. F
19. T
20. T

Chapter 8 Review, pp. 404–409

1. a
2. a
3. d
4. b
5. a
6. d
7. d
8. d
9. d
10. F
11. F
12. T
13. T
14. F
15. T
16. T
17. T
18. F

19. (a) iii
    (b) v
    (c) ii
    (d) i
    (e) iv
44. 2.5×10^{-7} cm
47. 3′-GCTTCG-5′
52. (a) 7896 bp
    (e) BamHI
53. (b) 1.1 and 1.3 kbp fragments
54. 1024 cuts; 1 cut every 195.3 bp
57. (b) functional genomics
59. BamHI
62. no

Unit 3 Self-Quiz, pp. 412–413

1. a
2. c
3. c
4. b
5. c
6. c
7. a
8. b
9. c
10. b
11. a
12. d
13. d
14. c
15. a
16. d
17. d
18. a
19. T
20. F
21. F
22. F
23. F
24. T
25. F
26. F
27. T
28. F
29. F
30. T
31. T
32. F
33. F
34. T
35. T
36. T
37. F
38. T
39. T
40. T
41. F
42. F

Unit 3 Review, pp. 414–421

1. d
2. b
3. d
4. a
5. d
6. c
7. a
8. d
9. b
10. c
11. b
12. d
13. d
14. a
15. c
16. a
17. d
18. T
19. T
20. F
21. T
22. F
23. F
24. T
25. T
26. T
27. T
28. F
29. T
30. F
31. F
32. T
33. T
34. F

35. (a) iii
    (b) v
    (c) ii
    (d) i
    (e) vi
    (f) iv
36. (a) vi
    (b) iv
    (c) i
    (d) v
    (e) iii
    (f) ii
37. (a) v
    (b) iv
    (c) ii
    (d) vi
    (e) iii
    (f) i

54. Met Phe Pro Pro
66. all correct
68. 1.16 mm
72. (a) ubiquitin: 8.2 s, titin: 1.03 h
77. (a) 1000 times
    (b) 1.85×10^{12} years
    (c) 2.22×10^{18} years
84. (a) prokaryotes

Unit 4

Are You Ready? pp. 424–425

7. (a) i; vi
    (b) iii; v
    (c) iv; vi
    (d) ii; iii
    (e) iii
    (f) vii
    (g) i
11. (a) systolic measurement/diastolic measurement
    (b) no; higher
14. atoms; molecules; organelles; cells; tissues; organs; systems; organism
15. (b) epithelial, connective, muscle, nervous
23. (a) 36.2 to 37.2 °C
    (b) 60 to 90 bpm
    (c) 12 to 20 breaths/min

9.2 Questions, p. 435

1. stimulus; sensor; integrator; effector; response
3. (a) yes
    (b) no
    (c) yes
    (d) no
    (e) yes
13. positive

9.4 Questions, p. 445

6. carnivore; carnivore
12. protein

Chapter 9 Self-Quiz, p. 459

1. d
2. c
3. b
4. b
5. b
6. a
7. c
8. d
9. b
10. F
11. T
12. F
13. T
14. F
15. F
16. F
17. F

Chapter 9 Review, pp. 460–465

1. b
2. a
3. a
4. b
5. c
6. a
7. b
8. d
9. b
10. T
11. F
12. F
13. F
14. T
15. F
16. F
17. F

18. (a) iii
    (b) v
    (c) i
    (d) ii
    (e) iv
19. (a) iv
    (b) v
    (c) ii
    (d) iii
    (e) i
29. ammonia; urea; uric acid
34. (a) 1: cortex; 2: medulla; 3: nephron; 4: renal pelvis
    (b) B: renal vein
    (c) 2: medulla
42. (b) kidneys
45. urea
49. temperature, permeability
50. (a) Malpighian tubules
    (b) uric acid
59. (a) filtration
    (b) glomerulus
    (c) proteins and cells
67. (a) incorrect

10.1 Questions, p. 472

2. protein hormones; steroid hormones

10.2 Questions, p. 482

1. thyroid hormones
2. adrenal hormones
6. FSH; LH; PRL
9. pineal gland

10.3 Questions, p. 487

1. insulin; glucagon
2. excessive thirst; excessive urine production; increased appetite

10.5 Questions, p. 493

5. cortisol (steroid); insulin (non-steroid)

10.7 Questions, p. 503

1. female: estrogen, progesterone; male: testosterone
6. GnRH; FSH; LH; inhibin
11. hypothalamus-pituitary-gonadal axis

Chapter 10 Self-Quiz, p. 507

1. b
2. c
3. c
4. d
5. a
6. d
7. d
8. a
9. b
10. c
11. F
12. F
13. F
14. F
15. T
16. T
17. T
18. T
19. T
20. F

Chapter 10 Review, pp. 508–513

1. b
2. c
3. b
4. a
5. b
6. d
7. c
8. a
9. b
10. d
11. d
12. d
13. c
14. c
15. a
16. T
17. T
18. F
19. F
20. T
21. F
22. F
23. T
24. T
25. F
26. F

27. (a) v
    (b) iv
    (c) ii
    (d) vi
    (e) i
    (f) iii
28. (a) vi
    (b) iv
    (c) i
    (d) v
    (e) iii
    (f) ii
31. (a) thyroid gland
32. glucocorticoids
34. (a) centre of the brain
    (b) secrete melatonin
35. insulin; glucagon; cortisol; epinephrine; norepinephrine
38. natural hormone
48. (a) pancreas H
    (b) thyroid F
    (c) pineal gland E
    (d) hypothalamus A; pituitary gland B
    (e) ovaries D
    (f) pituitary gland B
    (g) pituitary gland B
    (h) pituitary gland B
49. (c) gonadotropic hormones
54. (a) A
    (b) D
    (c) B
57. advantage
59. protein hormone
61. (a) anterior pituitary; thyroid glands
    (b) hypothyroidism

11.1 Questions, p. 521

3. glial cells, Schwann cells

11.3 Questions, p. 536

1. forebrain, midbrain, hindbrain

11.5 Questions, p. 548

2. mechanoreceptors; photoreceptors; chemoreceptors; thermoreceptors; nociceptors

Chapter 11 Self-Quiz, p. 559

1. b
2. d
3. c
4. c
5. b
6. d
7. b
8. a
9. d
10. F
11. T
12. F
13. F
14. T
15. T
16. F
17. T
18. F
19. T
20. F

Chapter 11 Review, pp. 560–565

1. c
2. a
3. b
4. a
5. b
6. c
7. d
8. a
9. a
10. c
11. d
12. b
13. F
14. F
15. F
16. T
17. F
18. T
19. F
20. F
21. F
22. T
23. F
24. T

25. (a) v
    (b) i
    (c) ii
    (d) iv
    (e) iii
26. (a) iii
    (b) v
    (c) i
    (d) ii
    (e) iv
27. reception; transmission; integration; response
28. afferent; interneurons; efferent
31. gap junction
33. (a) −50 to −55 mV
36. frontal; parietal; temporal; occipital
45. afferent neuron; interneuron; efferent neuron
48. (a) chemical synapse; gap junction
    (b) C
    (c) A
51. (a) I
    (b) E
    (c) C
57. (a) D
    (b) A
58. graph (c)
59. low dopamine
60. cerebellum
65. A or C

Unit 4 Self-Quiz, pp. 568–569

1. b
2. a
3. c
4. d
5. a
6. d
7. a
8. a
9. d
10. b
11. b
12. b
13. a
14. b
15. d
16. b
17. b
18. c
19. b
20. a
21. b
22. T
23. F
24. F
25. F
26. T
27. T
28. T
29. F
30. T
31. F
32. T
33. F
34. T
35. F
36. T

Unit 4 Review, pp. 570–577

1. c
2. c
3. d
4. b
5. c
6. d
7. c
8. d
9. d
10. a
11. d
12. c
13. d
14. b
15. a
16. d
17. c
18. a
19. c
20. T
21. F
22. T
23. F
24. F
25. T
26. F
27. T
28. T
29. F
30. T
31. F
32. F
33. F
34. F
35. F
36. T
37. T

38. (a) iii
    (b) v
    (c) vi
    (d) i
    (e) vii
    (f) viii
    (g) ix
    (h) ii
    (i) x
    (j) iv
39. (a) v
    (b) i
    (c) ii
    (d) iii
    (e) iv
40. (a) v
    (b) iii
    (c) ii
    (d) iv
    (e) i
41. extracellular fluid
42. positive feedback
46. (a) angiotensin-converting enzyme
49. diabetes insipidus; ADH
51. pituitary; FSH
52. afferent neuron; interneuron; efferent neuron
53. (a) A: dendrites; B: cell body; C: axon; D: axon terminals; E: nucleus
    (b) brain; spinal cord; muscles; glands
    (c) dendrites
54. cerebellum
55. substantia gelatinosa
56. cones
57. nervous system

61. (a) A: proximal convoluted tubule; B: distal convoluted tubule; C: glomerulus; D: collecting duct; E: loop of Henle; F: peritubular capillaries
   (b) D or B
   (c) C
   (d) it is reabsorbed
   (f) glucose
   (g) proteins
67. d, f, a, c, g, b, e
68. occipital
74. (a) sample B
   (b) sample D
   (c) sample C
77. (a) protein; unknown substance
   (b) red blood cells
   (d) collecting duct
78. (a) gestational diabetes
79. (a) all-or-nothing principle
81. incorrect
82. endorphins, serotonin
89. (a) adrenal medulla; epinephrine
90. (a) incorrect

Unit 5

Are You Ready? pp. 580–581

1. (a) T
   (b) F
   (c) T
   (d) F
   (e) F
   (f) F
   (g) F
   (h) F
2. (a) ii
   (b) iii
   (c) i
   (d) iv
9. 1000 units
10. (b) density dependent: i, ii, vi; density independent: iii, iv, v, vii, viii
11. 149
12. open
13. (c) 500 000 cells

12.1 Questions, p. 592

1. (a) clumped; random; uniform
5. about 60 black bears
6. (a) 5.8 dandelions/m^2; about 9000 dandelions

12.2 Questions, p. 599

1. natality; mortality; immigration; emigration
2. (b) 0.703
6. (a) 7–9 months
   (b) 19–21 months
   (c) 0.171
   (d) Type III survivorship curve
7. food; sex ratio; generation time
8. 360

12.3 Questions, p. 609

6. (a) 292.5 per day
   (b) 1.533 days
   (c) 11 doubling times; 16.8 days
7. 93; 220; 320; 360; 370; 330; 0.0

12.4 Questions, p. 615

1. (a) density independent
   (b) density dependent
   (c) density independent
   (d) density dependent
   (e) density independent
   (f) density independent

12.5 Questions, p. 628

2. (a) mutualism
   (b) parasitism
   (c) predation
   (d) competition
   (e) herbivory
   (f) predation
   (g) commensalism

Chapter 12 Self-Quiz, p. 633

1. b
2. c
3. a
4. d
5. c
6. a
7. c
8. d
9. c
10. a
11. F
12. T
13. T
14. F
15. T
16. F
17. F
18. T
19. F
20. F

Chapter 12 Review, pp. 634–639

1. c
2. c
3. a
4. b
5. b
6. d
7. b
8. a
9. c
10. a
11. T
12. F
13. T
14. T
15. F
16. F
17. T
18. F
19. F
20. F
21. F

22. (a) v
   (b) i
   (c) vi
   (d) ii
   (e) iv
   (f) iii
27. 1.24 days
34. (a) 0.283 blue jays/ha
   (b) 0.538 blue jays/ha
35. (a) 1548 fish
42. 10.397 aphids/day
43. about 27.6 years
48. (a) 11.8 %
50. density dependent
51. (c) no
   (d) long-term data
56. (b) no

Chapter 13 Self-Quiz, p. 681

1. c
2. a
3. d
4. b
5. d
6. c
7. d
8. b
9. F
10. T
11. F
12. F
13. T
14. T
15. F
16. F
17. F

Chapter 13 Review, pp. 682–687

1. b
2. c
3. c
4. d
5. b
6. d
7. c
8. a
9. a
10. c
11. a
12. d
13. T
14. F
15. F
16. T
17. T
18. F
19. T
20. T
21. T
22. F
23. T
24. T
25. T

26. (a) ii
   (b) iii
   (c) i
   (d) iv
27. (a) iii
   (b) iv
   (c) i
   (d) v
   (e) ii
   (f) vi
30. (a) C
   (b) E
   (c) D
   (d) 200 years ago
35. 9900 J
41. 10 %, 1 °C
46. industrial stage
60. (a) (i) E, (ii) F, (iii) D
   (b) country C
   (c) country B
   (d) country B

Unit 5 Self-Quiz, pp. 690–691

1. b
2. b
3. d
4. d
5. c
6. c
7. d
8. a
9. a
10. a
11. d
12. b
13. d
14. a
15. b
16. c
17. c
18. a
19. d
20. a
21. T
22. F
23. F
24. T
25. F
26. F
27. F
28. T
29. T
30. F
31. F
32. F
33. F
34. T
35. F

Unit 5 Review, pp. 692–699

1. d
2. c
3. c
4. b
5. b
6. a
7. d
8. c
9. a
10. d
11. a
12. c
13. b
14. a
15. d
16. d
17. b
18. a
19. c
20. b
21. F
22. T
23. T
24. T
25. F
26. T
27. F
28. F
29. F
30. T
31. F
32. T
33. F
34. T
35. F
36. F
37. T
38. T
39. T
40. T

41. (a) iv
   (b) v
   (c) ii
   (d) i
   (e) iii
42. (a) v
   (b) iii
   (c) i
   (d) iv
   (e) ii
43. 45 ground squirrels/ha
44. 18 dandelions/m^2
46. 0.371
47. (a) 5 % per year
   (b) 0.05 prairie dogs/individual/year
48. 3 weeks
49. S-shaped or sigmoid curve
50. carrying capacity (K)
51. about 2 days
54. (a) commensalism
   (b) mutualism
62. (a) 1.5 %; 20 %
   (b) 2.16 % in 2 years; 3.73 % in 5 years; 9.29 % in 10 years
64. 40 years
67. 2300 butterflies
69. natality; mortality
70. 19.7 years
71. (a) 43 koi
   (b) 0.13
72. $r = 0.0078$
74. limiting factor
77. commensalism
91. (a) type III
   (b) type I
   (c) type II
93. density dependent
99. (b) 2030 to 2050
   (c) 50 to 60 years
102. no

Glossary

5′ cap a sequence of seven Gs that is added to the start of a pre-mRNA molecule; ribosomes recognize this site and use it as the site of initial attachment (p. 321)

A

Aboriginal peoples descendants of First Nation, Métis, or Inuit people (p. 648)

absorption spectrum a plot of the amount of light energy of various wavelengths that a substance absorbs (p. 216)

action potential the voltage difference across a nerve cell membrane when the nerve is excited (p. 524)

action spectrum a plot of the effectiveness of light energy of different wavelengths in driving a chemical process (p. 217)

activation energy (E_a) the minimum amount of energy that chemical reactants must absorb to start a reaction (p. 129)

active site a pocket or groove in an enzyme that binds its substrate (p. 50)

active transport the movement of substances across membranes against their concentration gradient using pumps (p. 93)

aerobic cellular respiration a process that uses oxygen to harvest energy from organic compounds (p. 168)

afferent arteriole a vessel that supplies blood to the nephrons in the human kidney (p. 449)

afferent neuron a neuron that carries impulses from sensory receptors to the central nervous system; also called a sensory neuron (p. 516)

afferent system the component of the peripheral nervous system that receives input through receptors and transmits the input to the central nervous system (p. 519)

age-specific mortality the proportion of individuals that were alive at the start of an age interval but died during the age interval (p. 594)

age-specific survivorship the proportion of individuals that were alive at the start of an age interval and survived until the start of the next age interval (p. 594)

alcohol fermentation a process in which pyruvate is decarboxylated, producing a molecule each of CO_2 and of ethanol, and an NAD^+ (p. 191)

Allee effect a density-dependent phenomenon that occurs when a population cannot survive or fails to reproduce enough to offset mortality once the population density is too low (p. 612)

allosteric regulation the regulation of one site of a protein by binding to another site on the same protein (p. 53)

allosteric site a binding site on an enzyme that binds regulatory molecules (p. 53)

alternative splicing a process that produces different mRNAs from pre-mRNA (exons and introns), allowing more than one possible polypeptide to be made from a single gene (p. 322)

amino acid a molecule that contains a carboxyl group and an amino group; serves as the monomer subunit of proteins (p. 39)

aminoacyl–tRNA a molecule of transfer RNA bound to its associated amino acid (p. 326)

aminoacylation the process by which a tRNA molecule is bound to its corresponding amino acid (p. 326)

amniocentesis a genetic sampling method for testing *in utero* (p. 393)

amyloplast an organelle that stores starch (p. 77)

anabolic pathway a pathway in which energy is supplied to build complex molecules from simple molecules (p. 139)

anaerobic respiration a process that uses a final inorganic oxidizing agent other than oxygen to produce energy (p. 170)

androgens predominantly male sex hormones, including testosterone, that control sexual development and reproduction (p. 496)

anion an ion that has a negative charge (p. 12)

antenna complex a cluster of light-absorbing pigments embedded in the thylakoid membrane able to capture and transfer energy to special chlorophyll *a* molecules in the reaction centre (p. 216)

anticodon the complementary sequence of base pairs on a tRNA that corresponds to a codon on an mRNA (p. 325)

antiparallel oriented in opposite directions (p. 46)

aquaculture a method of raising fish and shellfish for crops (p. 661)

aquaporin a membrane protein that passively transports water molecules (p. 451)

ATP cycle the cyclic and ongoing breakdown and re-synthesis of ATP (p. 144)

autoionization the process in which a molecule spontaneously dissociates into ions (p. 21)

autonomic system a subdivision of the efferent system (within the PNS); regulates the internal environment (p. 519)

axon an extension of cytosol that carries nerve signals away from the nerve cell body (p. 517)

B

bacteriophage a virus that infects bacteria (p. 275)

basal metabolic rate (BMR) the metabolic rate of an organism at rest (p. 185)

beta-oxidation a process in which fatty acids are broken down into acetyl-CoA through catabolism (p. 188)

biocapacity a measure of an ecosystem's ability to produce useful biological materials and to absorb waste materials created by humans (p. 669)

bioinformatics the use of computer technology to process a large amount of biological data (p. 382)

biopharming a process in which genetically engineered host organisms are used to make pharmaceuticals or other products that are useful to humans (p. 386)

blood–brain barrier a barrier formed by tight junctions between endothelial cells in the capillaries in the brain that blocks the movement of most substances into the brain via the bloodstream (p. 534)

blunt end the end that remains after restriction enzymes cut straight across a DNA strand; a blunt end is more difficult than a sticky end to recombine with another strand (p. 367)

bond energy the minimum amount of energy that is required to break a particular type of bond; measured in kJ/mol of bonds (p. 128)

Bowman's capsule a small folded structure in the human kidney that encircles the glomerulus (p. 449)

buffer a chemical that compensates for pH changes in a solution by accepting or donating H^+ ions (p. 23)

bycatch marine and aquatic species that are captured because of their proximity to targeted species (p. 661)

C

C_4 cycle an alternative form of carbon fixation that some plants use, particularly in hot weather, to increase the concentration of CO_2 available for the Calvin cycle reactions (p. 232)

Calvin cycle the second stage of the photosynthesis process that uses ATP and NADPH to convert CO_2 to sugars (p. 213)

carbohydrate a biomolecule that consists of carbon, oxygen, and hydrogen (p. 29)

carrier protein a protein that binds to a molecule and transports it across the lipid bilayer (p. 91)

carrying capacity (*K*) the number of individuals in a population that the environmental resources can support (p. 605)

catabolic pathway a pathway in which energy is released and complex molecules are broken down into simple molecules (p. 139)

cation an ion that has a positive charge (p. 12)

cell junction a structure that allows cells to interact with each other and the surrounding environment (p. 79)

cell senescence the period in a cell's lifespan when it loses the ability to divide and grow; often referred to as cell aging (p. 296)

cell wall the outer barrier of a plant cell; the cell wall surrounds the plasma membrane and gives structure to the plant (p. 79)

central dogma the fundamental principle of molecular genetics, which states that genetic information flows from DNA to RNA to proteins (p. 313)

central nervous system (CNS) the body's coordinating centre for mechanical and chemical actions; made up of the brain and spinal cord (p. 518)

cerebellum the hindbrain region that is involved in muscle movement and balance (p. 531)

cerebral cortex the outermost layer of the cerebral hemispheres (p. 532)

cerebrospinal fluid circulating fluid that surrounds the membranes of the brain and spinal cord; provides neural connection to the endocrine system (p. 530)

cerebrum the brain region that is involved in motor activities and sensory information; the largest and most developed region of the brain (p. 532)

channel protein a hydrophilic pathway in a membrane that enables water and ions to pass through (p. 90)

chemical synapse a synapse in which a neurotransmitter moves from a presynaptic cell to a postsynaptic cell through the synaptic cleft (p. 522)

chemiosmosis a process in which ATP is synthesized using the energy of an electrochemical gradient and the ATP synthase enzyme (p. 180)

chloroplast a double membrane–bound organelle that contains enzymes and pigments that are used to perform photosynthesis in eukaryotic cells (p. 77)

chromoplast an organelle that makes and stores pigments other than chlorophyll (p. 77)

cilia tiny hairlike structures that move water and mucus in eukaryotes; used for movement of prokaryotic cells (p. 78)

citric acid cycle a cyclic series of reactions that transfers energy from organic molecules to ATP, NADH, and $FADH_2$ and releases carbon atoms as CO_2 (p. 169)

cloned gene an identical copy of an original target gene that can be made by introducing the target gene into a host cell and having it copied (p. 368)

coding strand the DNA strand that is not being copied but contains the same sequence as the new RNA molecule (p. 319)

codon a group of three base pairs that code for an individual amino acid (p. 317)

coenzyme an organic molecule that acts as a cofactor of an enzyme (p. 52)

coevolution a process in which one species evolves in response to the evolution of another species (p. 616)

cofactor a non-protein group that binds to an enzyme and is essential for catalytic activity (p. 52)

cohort a group of individuals of similar ages (p. 593)

commensalism an interaction in which one species benefits and the other is unaffected (p. 616)

comparative genomics the study of the organization, functions, and relationships of the genomes of different species (p. 347)

competent cell a cell that is able to take up foreign DNA from its surroundings (p. 368)

competition an interaction in which both competing populations lose access to some resources (p. 610)

competitive inhibition a situation in which a competitor substance binds to a normal substrate binding site to block enzyme activity (p. 53)

complementary base pairing the chemical tendency of adenine to form hydrogen bonds with thymine, and cytosine to form hydrogen bonds with guanine (p. 278)

complex carbohydrate a molecule that is composed of hundreds to thousands of monosaccharides linked together; an essential part of nutrition and a valuable energy source (p. 31)

contractile vacuole a structure in a single-celled organism that maintains osmotic equilibrium by pumping excess fluid out of the cell (p. 446)

copy number the number of plasmids of a specific type within a cell (p. 368)

corepressor a signal molecule that binds to a regulatory protein to reduce the expression of an operon's genes (p. 334)

cranial nerves the 12 pairs of nerves within the parasympathetic division of the autonomic system, which emerge directly from the brain and serve the head, neck, and body trunk (p. 538)

crassulacean acid metabolism (CAM) a metabolic pathway, used mostly by succulent plants, in which the Calvin cycle and the C_4 cycle are separated in time for better efficiency of CO_2 fixation (p. 233)

crude density population density measured in terms of the number of organisms of the same species within the total area of the entire habitat (p. 585)

cytoskeleton a dynamic system of filaments that provides cell structure, helps with cell division, and enables the cell and inner organelles to move around (p. 77)

D

decarboxylation reaction a chemical reaction that removes a carboxyl group to form CO_2 (p. 175)

dehydration reaction a chemical reaction in which subunits of a larger molecule are joined by the removal of water; also called a condensation reaction (p. 16)

dehydrogenase an enzyme that oxidizes a substrate and transfers hydrogen ions to an acceptor (p. 154)

dehydrogenation the removal of a hydrogen atom from a molecule (p. 175)

deletion the removal of a base pair (small-scale mutation) or larger coding region (large-scale mutation) from a DNA sequence (p. 340)

demographic transition model a diagram that illustrates changes in how people live to explain shifts in population sizes (p. 650)

demography the study of the growth rate, age structure, and other characteristics of populations (p. 593)

denaturation the loss of both the structure and function of a protein (p. 43)

dendrite a projection of cytosol that carries signals toward the nerve cell body (p. 517)

density-dependent factor a factor that is influenced by population density, having a greater impact as the population density increases (p. 610)

density-independent factor a factor that influences population regulation regardless of population density (p. 610)

diabetes mellitus a disease in which the blood glucose level is too high because of the insufficient production or activity of the hormone insulin (p. 366)

disaccharide a carbohydrate molecule that is made from two monosaccharide units (p. 30)

dispersion the pattern of distribution in which a population exists; may be clumped, random, or uniform (p. 586)

distal convoluted tubule the duct portion of a nephron that connects the loop of Henle to the ducts that lead to the renal pelvis (p. 449)

DNA ligase an enzyme that catalyzes the formation of a phosphodiester bond between two DNA strands, as well as between Okazaki fragments (p. 286)

DNA microarray a solid surface that has a microscopic grid of many DNA fragments, called probes, attached; used to determine gene expression (p. 383)

DNA polymerase I a prokaryotic replication enzyme that fills in gaps in the lagging strand between Okazaki fragments; also proofreads the final strands (p. 286)

DNA polymerase II a prokaryotic replication enzyme that repairs damage to DNA, including damage that occurs between replication events (p. 286)

DNA polymerase III a prokaryotic replication enzyme that builds new DNA strands from nucleotides (p. 286)

DNA primer a short single-stranded DNA sequence, easily synthesized in a laboratory, that is complementary to a sequence at one end of the target sequence (p. 376)

DNA sequencing a process in which the sequence of base pairs in a DNA strand is determined (p. 379)

dynamic equilibrium the state in which continuous action results in balanced conditions (p. 89)

E

ecological deficit resource use and waste production that exceeds a sustainable level (p. 669)

ecological density population density measured in terms of the number of individuals of the same species per unit area or volume that is actually used by the individuals (p. 585)

ecological footprint the impact imposed on the environment by the demand for natural resources (p. 642)

ectotherm an animal that maintains its body temperature by absorbing thermal energy from the environment (p. 437)

effector the element (or elements) of a feedback system that acts to return the system to its optimal state (p. 432)

efferent arteriole a vessel that carries away filtered blood from the nephrons in the human kidney (p. 449)

efferent neuron a neuron that carries impulses from the central nervous system to skeletal muscles; also known as a motor neuron (p. 516)

efferent system the component of the peripheral nervous system that carries signals away to the effectors (muscles and glands) (p. 519)

electrical synapse a synapse in which the presynaptic cell makes direct contact with the postsynaptic cell, allowing current to flow via gap junctions between the cells (p. 523)

electrochemical gradient the combined effects of a difference in electrical potential energy and a difference in the concentration gradients of ions (p. 94)

electronegativity the measure of an atom's attraction to shared electrons (p. 13)

emigration the movement of individuals out of a population (p. 593)

endergonic reaction a chemical reaction that absorbs free energy; the products have more free energy than the reactants (p. 138)

endomembrane system a group of interacting organelles between the nucleus and the plasma membrane (p. 74)

endoplasmic reticulum (ER) a membrane-bound organelle that is folded into flattened sacs and tubes, and is often an outgrowth of the nuclear envelope in a eukaryotic cell (p. 75)

endotherm an animal that maintains its body temperature by internal mechanisms (p. 437)

endothermic reaction a chemical reaction in which energy is absorbed, giving the products more chemical potential energy than the reactants (p. 129)

energy coupling the transfer of energy from one reaction to another in order to drive the second reaction (p. 138)

energy pyramid a tool that is used by researchers to track the usable energy in a food web (p. 658)

entropy a measurement of disorder in a system (p. 134)

enzyme a biological catalyst, usually a protein, that speeds up a chemical reaction (p. 50)

epidemic the spread of a disease beyond a very local population (p. 644)

estivation a state of torpor that enables an animal to survive the summer by reducing the demand for energy (p. 440)

estrogens predominantly female sex hormones, including estradiol, that trigger sexual development (p. 490)

ethidium bromide a large molecule that resembles a base pair, which allows it to insert itself into DNA; used for staining electrophoresis gels (p. 379)

exergonic reaction a chemical reaction that releases free energy; the products have less free energy than the reactants (p. 137)

exon a sequence of DNA or RNA that codes for part of a gene (p. 322)

exothermic reaction a chemical reaction in which energy is released, leaving the products with less chemical potential energy than the reactants (p. 129)

exploitative competition competition in which all the individuals have equal access to resources; some have superior ability to gather resources (p. 621)

exponential model of population growth a pattern of population growth in which organisms reproduce continuously at a constant rate (p. 600)

extracellular matrix (ECM) a molecular system that supports and protects a cell; a cell's environment (p. 79)

F

facilitated diffusion the facilitated transport of ions and polar molecules through a membrane via protein complexes (p. 90)

facultative anaerobe an organism that can live with or without oxygen (p. 170)

fatty acid a molecule that consists of a carboxyl group and a hydrocarbon chain (p. 33)

fecundity the potential for a species to produce offspring in a lifetime (p. 596)

feedback inhibition the regulation of a pathway by one of the products of this pathway (p. 54)

fermentation a process that uses an organic compound as the final oxidizing agent to produce energy (p. 170)

filtration the process in which blood and fluid pass through a selectively permeable membrane (p. 451)

first law of thermodynamics principle that states that energy can be transferred or transformed, but it cannot be created or destroyed (p. 127)

flagellum a whiplike tail that is used in propulsion of both prokaryotic and eukaryotic cells (p. 78)

fluid mosaic model the idea that a biological membrane consists of a fluid phospholipid bilayer, in which proteins are embedded and float freely (p. 82)

frameshift mutation a shift in the reading frame resulting in multiple missense and/or nonsense effects (p. 340–341)

free energy energy that can do useful work; also called Gibbs free energy (p. 136)

functional genomics the study of the functions of genes, the proteins they make, and how these proteins function (p. 382)

functional group a group of atoms that affects the function of a molecule by participating in chemical reactions (p. 26)

fundamental niche the range of conditions and resources that a population can possibly tolerate and use (p. 622)

G

gel electrophoresis a method for separating large molecules, such as DNA, RNA, and proteins (p. 378)

gene therapy the insertion, removal, or replacement of genes (to correct defective genes) within an organism's cells to treat a disease (p. 391)

generation time the average time between the birth of an organism and the birth of its offspring (p. 597)

genetic code the specific coding relationship between bases and the amino acids they specify; the genetic code can be expressed in terms of either DNA or RNA bases (p. 316)

genetic engineering the intentional production of new genes and alteration of genomes by the substitution or introduction of new genetic material (p. 366)

genetic screening biochemical or molecular tests that are used to identify inherited disorders in parents, potential parents, embryos, or children after they are born (p. 393)

genome the complete set of an organism's hereditary information (p. 271)

geographic range the overall spatial boundaries within which a population lives (p. 584)

germ-line gene therapy a process in which germ cells (sperm cells or eggs) are modified by integrating functional genes into their genomes (p. 391)

glial cell a non-conducting cell that is important for the structural support and metabolism of nerve cells (p. 518)

glomerulus a network of capillaries within the Bowman's capsule that performs the first step in the filtration of blood (p. 449)

glucagon a hormone produced by alpha cells in the pancreas that raises the blood glucose level by promoting the breakdown of glycogen in the liver (p. 469)

glycolipid any membrane lipid that is bound to a carbohydrate (p. 82)

glycolysis a series of reactions in which a glucose molecule is broken into two pyruvate molecules and energy is released (p. 169)

glycoprotein a membrane component that contains a sugar, or carbohydrate, bound to an amino acid (p. 82)

glycosidic bond a bond between two monosaccharides (p. 30)

Golgi body an organelle with folded membranes where the final packaging of proteins occurs (p. 76)

gonadotropin-releasing hormone (GnRH) a hormone released by the hypothalamus that controls the release of LH and FSH from the anterior pituitary, which, in turn, control the synthesis and release of the male or female sex hormones in the gonads (p. 496)

gonads glands responsible for the production of sex hormones, as well as the egg and sperm cells; called testes in males and ovaries in females (p. 496)

grey matter the tissue of the brain and spinal cord where the cell bodies and dendrites of neurons are located (p. 531)

H

habitat the place where an organism normally lives (p. 584)

Hayflick limit the total number of times that a normal cell can divide (p. 296)

helicase a replication enzyme that separates and unwinds the DNA strands (p. 283)

herbivory the interaction between herbivorous animals and the plants that they eat (p. 616)

hibernation a state of greatly reduced metabolic rate and activity that enables an animal to survive the winter by reducing the demand for energy when food is unavailable (p. 440)

histone a special protein molecule that is the core around which the DNA strand wraps (p. 271)

homeostasis the physiological state of the body in which internal physical and chemical conditions are kept within a range that is suitable for life processes (p. 428)

homeostatic mechanism a system that monitors internal and external conditions and changes bodily functions to maintain homeostasis (p. 430)

homeotherm an animal that maintains a stable body temperature regardless of the temperature of the external environment (p. 437)

host cell a cell that has taken up a foreign plasmid or virus and has used its cellular machinery to express the foreign DNA (p. 368)

Human Genome Project the joint government and private sector research project that sequenced the human genome (p. 346)

hybridization probe a fragment of DNA that is used to detect the presence of complementary nucleotide sequences (p. 374)

hydrogen bond the attractive force between a partially positively charged hydrogen atom and a partially negatively charged atom in another molecule (p. 15)

hydrolysis reaction a chemical reaction in which water is used as a reactant to split a larger molecule into smaller subunits (p. 17)

hydrophilic molecules polar or charged molecules that are strongly attracted to water (p. 21)

hydrophobic molecules non-polar molecules that are not strongly attracted to water (p. 21)

hyperosmotic the property of the solution on one side of a selectively permeable membrane that has the lower concentration of water (p. 442)

hypertonic the property of a solution that has a higher solute concentration than another solution (p. 92)

hypoosmotic the property of the solution on one side of a selectively permeable membrane that has the higher concentration of water (p. 442)

hypothalamus the region of the brain that releases hormones to control the pituitary gland, which, in turn, controls other endocrine glands (p. 473)

hypotonic the property of a solution that has a lower solute concentration than another solution (p. 92)

I

immigration the movement of individuals into a population (p. 593)

induced-fit model a model of enzyme activity that describes how an enzyme changes shape to better accommodate a substrate (p. 50)

induced mutation a mutation that is caused by an environmental agent (p. 342)

inducer a signal molecule that triggers the expression of an operon's genes (p. 333)

Industrial Revolution a period of great technological advancement from the 1800s to 1900s, during which machines were developed (p. 645)

industrialized agriculture the growth of food using machines and synthetic fertilizers and pesticides (p. 656)

insertion the addition of a base pair (small-scale mutation) or larger coding region (large-scale mutation) to a DNA sequence (p. 340)

insulin a hormone produced in the pancreas that lowers the blood glucose level by promoting the uptake of glucose by the body cells (p. 332)

integral membrane protein a protein that is embedded in the lipid bilayer (p. 85)

integrator the element of a feedback system that compares existing conditions with ideal conditions (p. 332)

interference competition competition in which all the individuals have equal access to resources; the fitness of some individuals is reduced by the presence of others (p. 621)

intermolecular force the force of attraction between two molecules (p. 15)

internal environment the extracellular fluid, which consists of the fluid that surrounds the cells and tissues in the body and the plasma portion of the blood (p. 429)

interneuron a local circuit neuron of the central nervous system that relays impulses between afferent (sensory) and efferent (motor) neurons (p. 516)

interspecific competition competition between members of different species (p. 610)

interstitial fluid the fluid that surrounds the body cells (p. 429)

intraspecific competition competition between members of the same population for resources (p. 610)

intron a non-coding sequence of DNA or RNA (p. 322)

inversion two adjacent bases trading places (small-scale mutation) or the reversal of a sequence of DNA (large-scale mutation) (p. 340)

ion channel a protein embedded in the plasma membrane that allows ions to pass through it (p. 523)

ionic bond a bond that results from the attraction between two oppositely charged atoms or molecules (p. 12)

islets of Langerhans endocrine cell clusters inside the pancreas that produce insulin and glucagon (p. 483)

isomer a molecule that has the same composition as another, but a different arrangement of atoms (p. 29)

isoosmotic the property of two solutions that have equal water concentrations (p. 442)

isotonic the property of a solution that has the same solute concentration as another solution (p. 92)

isotope a form of an element that differs in its number of neutrons (p. 9)

K

kinetic energy the energy of motion (p. 126)

L

***lac* operon** a cluster of genes that contains the DNA sequences to regulate the metabolism of lactose (p. 332)

lactate fermentation a process in which pyruvate reacts with NADH and is converted directly into lactate and regenerates NAD^+ (p. 192)

lagging strand the DNA strand that is copied in the direction away from the replication fork (p. 286)

leading strand the DNA strand that is copied in the direction toward the replication fork (p. 286)

life table a chart that summarizes the demographic characteristics of a population (p. 593)

light-dependent reactions the first stage of photosynthesis, during which water molecules are split as light energy is absorbed and transformed into chemical energy in ATP and NADPH (p. 212)

limiting factor a factor that limits the growth of a population (p. 610)

LINEs (long interspersed nuclear elements) repetitive DNA sequences, approximately 6500 bp in length on average, interspersed throughout the genome (p. 347)

lipid a non-polar compound that is made mostly of carbon and hydrogen (p. 33)

logistic model of population growth a model that describes limited population growth, often due to limited resources or predation (p. 605)

loop of Henle the U-shaped part of the duct that connects the proximal convoluted tubule to the distal convoluted tubule (p. 449)

lysosome a small, membrane-bound organelle that contains digestive enzymes that aid in waste disposal (p. 76)

M

malnutrition a condition that develops when the body lacks proper nutrients (p. 655)

Malpighian tubule the main organ of excretion in insects, which is used to carry wastes to the intestines (p. 447)

mark-recapture method a sampling technique for estimating population size and density by comparing the proportion of marked and unmarked animals that are captured in a given area; sometimes called the capture-recapture method (p. 589)

medulla oblongata the hindbrain region that connects the spinal cord to the cerebellum; important in autonomic nerve control (p. 531)

membrane potential the electrical potential of a membrane, which is caused by an imbalance of charges on either side of the membrane (p. 523)

meninges three layers of connective tissue that surround and protect the brain and spinal cord (p. 530)

menopause the end of a female's reproductive capability, after which menstruation ceases and female hormone levels drop (p. 497)

menstrual cycle the monthly cycle of events in a sexually mature female that prepares the uterus for the implantation of a fertilized egg (p. 497)

messenger RNA (mRNA) the end product of the transcription of a gene; mRNA is translated by ribosomes into a protein (p. 315)

metabolic rate the amount of energy that is expended per unit time in an organism (p. 185)

metabolism the sum of all chemical reactions in a cell or organism (p. 126)

metanephridium an excretory organ in some invertebrates that is used to reabsorb and eliminate wastes (p. 446)

microfilament a fibre structure made from actin that is part of the cytoskeleton and is located in the cytosol of cells (p. 78)

mimicry a form of defence in which one species evolves an appearance that resembles the appearance of another species (p. 618)

minimum viable population size the smallest population size that is likely to survive both predictable and unpredictable environmental variation; note that it is only a prediction (p. 613)

missense mutation a mutation that changes a single amino acid in the coding sequence (p. 340–341)

mitochondrion an organelle with two membranes; the site of most ATP synthesis during aerobic cellular respiration (p. 76)

mole the number (approximately 6.022×10^{23}) of atoms or molecules whose mass in grams is equal to the atomic mass of one such particle in atomic mass units; one carbon atom has a mass of 12 AU, and, therefore, one mole of carbon atoms has a mass of 12 g (p. 128)

molecular marker a fragment of a known size that is run as a comparison standard for gel electrophoresis (p. 379)

monomer a small molecule that can bind chemically to other molecules (p. 31)

monosaccharide the simplest form of carbohydrate, consisting of a single sugar unit; a building block for more complex carbohydrates (p. 29)

mortality the death rate in a population (p. 593)

mutagen an environmental agent that directly alters the DNA within a cell (p. 342)

mutualism an interaction in which both partners benefit (p. 616)

myelin sheath an insulated covering over the axon of a nerve cell (p. 518)

N

NADH the reduced form of the coenzyme nicotinamide adenine dinucleotide (p. 154)

natality the birth rate in a population (p. 593)

negative feedback the response of a system that acts to maintain equilibrium by compensating for any changes made to the system (p. 432)

nephron the tiny functional unit of the kidney that filters wastes from the blood (p. 448)

neural circuit the coordination of the receptor, afferent neuron, interneuron, efferent neuron, and effector in response to a stimulus (p. 520)

neural signalling the reception, transmission, and integration of nerve impulses by neurons, and the response to these impulses (p. 516)

neurohormone a hormone produced by neurons, such as in the hypothalamus, that controls the production of other hormones in the pituitary gland (p. 473)

neuron a nerve cell that is capable of conducting nerve impulses (p. 516)

neurotransmitter a chemical that is released from vesicles into synapses to facilitate nerve signal transmission (p. 522)

neutralization reaction a reaction in which an acid and a base combine to create a salt and water (p. 17)

node of Ranvier a regularly occurring gap between sections of myelin sheath along the axon (p. 518)

noncompetitive inhibition a situation in which molecules bind to an enzyme at a site that is not the active site, thus blocking enzyme activity (p. 53)

nonsense mutation a mutation that results in a premature stop codon (p. 340–341)

nuclear envelope a two-layer membrane that encloses the nucleus of a eukaryotic cell (p. 73)

nucleic acid a blueprint for proteins that are synthesized in cells; stores hereditary information (p. 39)

nucleoside triphosphate a building block and energy source for replicating DNA (p. 285)

nucleosome a unit of DNA storage, consisting of eight histones with DNA strands wrapped around them; the DNA around each nucleosome is about 147 nucleotides in length (p. 291)

nucleotide the building block of nucleic acids; consists of a 5-carbon sugar, a nitrogenous base, and one to three phosphate groups (p. 45)

O

obligate aerobe an organism that cannot live without oxygen (p. 168)

obligate anaerobe an organism that cannot survive in the presence of oxygen (p. 170)

Okazaki fragment the piece of new DNA on the lagging strand (p. 286)

one gene–one enzyme hypothesis the hypothesis, proposed by Beadle and Tatum, that each gene is unique and codes for the synthesis of a single enzyme (p. 313)

one gene–one polypeptide hypothesis the hypothesis that each gene is unique and codes for the synthesis of a single polypeptide; the restated version of the one gene–one enzyme hypothesis (p. 313)

oogenesis the production of eggs, or ova, from oocytes in the ovaries by two meiotic divisions (p. 496)

operator the region in the operon that regulatory factors bind to (p. 332)

orbital a region of space that is occupied by electrons located around the nucleus of an atom (p. 11)

organelle an internal functional structure that is located within the cytosol of a cell (p. 72)

organic agriculture a method of growing food without using synthetic fertilizers or pesticides (p. 660)

osmoregulation the process of actively regulating the osmotic pressure of bodily fluids and cells (p. 443)

osmosis the passive diffusion of water across a membrane (p. 91)

osmotic pressure the pressure that results from a difference in solute concentration between the two sides of a selectively permeable membrane (p. 442)

oxidation a reaction in which a molecule loses electrons (p. 17)

oxidative phosphorylation a process that forms ATP using energy transferred indirectly from a series of redox reactions (p. 169)

P

parasitism an interaction in which one species benefits and the other is harmed (p. 616)

parasympathetic division one of two subdivisions of the autonomic nervous system; stimulates body activities that acquire and conserve energy (p. 519)

parathyroid hormone a hormone secreted by the parathyroid glands that controls calcium and phosphate levels in the blood (p. 479)

passive transport the movement of a substance across a membrane without expending energy (p. 89)

pathogen a disease-causing agent, such as a microbe or fungus (p. 644)

peptide a chain of amino acid subunits that are connected by peptide bonds (p. 41)

peptide bond a covalent bond that links amino acids (p. 41)

per capita growth rate (*r*) the difference between the per capita birth rate and the per capita death rate of a population (p. 601)

peripheral membrane protein a protein on the surface of the membrane (p. 85)

peripheral nervous system (PNS) all parts of the nervous system, excluding the brain and spinal cord; relays information between the central nervous system and other parts of the body (p. 518)

peritubular capillaries a net of capillaries in the nephrons that reabsorb essential ions and minerals from filtered blood (p. 449)

phosphodiester bond a link that is formed between nucleotides by a phosphate bridge (p. 45)

phospholipid a lipid that consists of two fatty acids and a phosphate group bound to glycerol (p. 35)

phosphorylation the transfer of a phosphate group, usually from ATP, to another molecule (p. 142)

photoautotroph an organism that makes its own food using energy from the Sun (p. 212)

photorespiration the catalysis of O_2 instead of CO_2 by rubisco into RuBP, which slows the Calvin cycle, consumes ATP, and results in a release of carbon (p. 231)

photosystem I a collection of pigment proteins that includes chlorophyll *a* and absorbs light at the 700 nm wavelength (p. 218)

photosystem II a collection of pigment proteins that includes chlorophyll *a* and absorbs light at the 680 nm wavelength (p. 218)

pineal gland an endocrine gland located in or on the brain of vertebrates that secretes the hormone melatonin to regulate biological rhythms (p. 480)

pituitary gland a two-lobed gland within the cranial cavity that produces hormones that control the other endocrine glands (p. 474)

plasma membrane a dynamic barrier that surrounds the cytosol of the cell (p. 72)

plasmid a small circular section of DNA found in the cytosol of bacteria; replicates independently of the chromosomal DNA (p. 271)

plastid a membrane-bound organelle that is involved in photosynthesis and storage in plants and algae (p. 77)

poikilotherm an animal whose body temperature varies with, and often matches, the temperature of the external environment (p. 437)

point mutation a change in a single nucleotide within a gene (p. 340)

polar covalent bond a bond between two atoms, made up of unequally shared electrons (p. 14)

polarity partial positive or negative charge at the ends of a molecule (p. 14)

poly(A) tail a chain of adenine nucleotides that are added to the 3′ end of the pre-mRNA molecule to protect it from enzymes in the cytosol (p. 321)

polymer a large molecule that is formed when monomers link together chemically in a chain (p. 31)

polymerase chain reaction (PCR) a process that is used to make a huge number of copies of a DNA sequence in a laboratory, quickly and without the need for a host organism (p. 376)

polymerization a process in which small subunits are linked to form a large molecule (p. 31)

polypeptide a peptide with more than 50 amino acids (p. 41)

polysaccharide molecule a molecule that contains many linked monosaccharides (p. 31)

polysome a complex that is formed when multiple ribosomes attach to the same mRNA molecule in order to facilitate rapid translation (p. 329)

pons the brain region that transfers nerve signals between the cerebellum and the medulla (p. 531)

population density (*D*) the number of individuals of the same species that occurs per unit area or volume (p. 585)

population dynamics the change in a population over time (p. 600)

population ecology a sub-field of ecology that focuses on the dynamics of populations and how populations interact with their environment (p. 584)

population pyramid a tool that shows the distribution of ages among males and females in a population (p. 647)

population size (N_t) the number of individuals of a specific species that occupies a given area or volume at a given time (p. 585)

positive feedback the response of a system that acts to increase the effect of any changes made to the system (p. 434)

potential energy the stored energy that an object possesses as a result of its position relative to other objects or to its internal structure (p. 126)

precursor mRNA (pre-mRNA) the initial RNA transcription product (p. 316)

predation the interaction between predator and prey (p. 610)

primary electron acceptor a molecule capable of accepting electrons and becoming reduced during photosynthesis (p. 215)

primary wall a cellulose coating that surrounds a plant cell (p. 79)

progestins predominantly female sex hormones, including progesterone, that control the menstrual cycle (p. 490)

promoter a nucleotide sequence that lies just before a gene and allows for the binding of RNA polymerase (p. 319)

protein a large molecule that consists of many amino acid subunits that are joined together by peptide bonds folded into a specific three-dimensional shape (p. 39)

protein hormone a hormone composed of chains of amino acids that is water soluble; usually acts on cell membrane receptors (p. 469)

proton gradient a difference in proton (H^+ ion) concentration across a membrane (p. 180)

proton-motive force a force that moves protons because of a chemical gradient (often referred to as an electrochemical gradient) of protons across a membrane (p. 180)

proximal convoluted tubule the duct portion of a nephron that connects the Bowman's capsule to the loop of Henle (p. 449)

pseudogene a sequence of DNA that is similar to an existing gene but does not code for proteins (p. 347)

purine a class of nitrogenous bases with a double-ring structure; adenine and guanine are purines (p. 276)

pyrimidine a class of nitrogenous bases with a single-ring structure; thymine and cytosine are pyrimidines (p. 276)

pyruvate oxidation a reaction in which pyruvate is oxidized by NAD^+, and CO_2 is removed, forming an acetyl group and releasing NADH (p. 169)

Q

quadrat a sampling frame that is used for estimating population size; the frame can be real or virtual (p. 588)

R

radioisotope a radioactive isotope of an element (p. 10)

reabsorption the transfer of water, ions, and nutrients back to the interstitial fluid via passive and active transport (p. 451)

reaction centre a complex of proteins and pigments that contains the primary electron acceptor (p. 216)

reading frame a particular system for separating a base-pair sequence into readable codons (p. 327)

realized niche the range of conditions and resources that a population actually uses in nature (p. 622)

recognition site a sequence of bases on a DNA strand that restriction enzymes bind to (p. 366)

recombinant DNA a DNA strand that is created using DNA pieces from two or more sources (p. 366)

redox reaction an electron transfer reaction (p. 17)

reduction a reaction in which a molecule gains electrons (p. 17)

reflex arc a neural circuit that travels through the spinal cord but does not require the coordination of the brain; allows for reflex actions (p. 520)

refractory period the period of time during which the threshold required for the generation of an action potential is much higher than normal (p. 525)

renin-angiotensin-aldosterone pathway a negative feedback mechanism that attempts to maintain blood pressure (p. 552)

replacement rate the rate at which people have children to "replace" them when they die (p. 651)

replication bubble the separating of DNA in both directions during replication (p. 284)

replication fork the point of separation of the two parent DNA strands during replication (p. 283)

replication origin a specific sequence of DNA that acts as a starting point for replication (p. 283)

repressor protein a protein that binds to the operator to repress gene transcription (p. 332)

resource partitioning a situation in which several species that live in the same place use different resources or use the same resources in different ways (p. 622)

resting potential the voltage difference across a nerve cell membrane of an unstimulated neuron; usually negative (p. 523)

restriction enzyme an enzyme that cuts DNA at a specific location in a base sequence; also called restriction endonuclease (p. 366)

restriction fragment a fragment that is produced when a DNA strand is cut by a restriction enzyme (p. 366)

restriction map a diagram that shows restriction enzyme recognition sites and the distances, measured in base pairs (bp), between the sites (p. 369)

retrovirus a virus that uses reverse transcriptase for replication (p. 351)

reverse transcriptase a viral enzyme that uses RNA as a template strand to synthesize complementary DNA (p. 351)

ribosomal RNA (rRNA) an RNA molecule within the ribosome that bonds the correct amino acid to the polypeptide chain (p. 315)

RNA polymerase an enzyme that reads a DNA strand and creates a complementary strand of RNA (p. 315)

RNA primase a replication enzyme that produces RNA primers (p. 286)

RNA primer a replication molecule that acts as a starting point for replication (p. 286)

rough ER areas of endoplasmic reticulum with ribosomes attached to the surface (p. 75)

rubisco ribulose-1,5-bisphosphate carboxylase oxygenase; a critical enzyme that acts as a catalyst for the reduction of carbon dioxide in the Calvin cycle of photosynthesis (p. 227)

S

salinization the addition of salt products due to the overuse of resources (p. 659)

saturated fat a lipid that is composed of saturated fatty acids with single bonds in their hydrocarbon chain (p. 35)

second law of thermodynamics principle that states that every time energy is converted to another form, some of the energy becomes unusable (p. 134)

secondary wall a coating that is added to a plant cell wall; it is more rigid and often thicker than the primary cell wall (p. 79)

secretion the removal of waste materials from the blood and intercellular fluid (p. 452)

semiconservative replication a mechanism of DNA replication in which each of the two strands of parent DNA is incorporated into a new double-stranded DNA molecule (p. 282)

sensor the element of a feedback system that detects changes in the environment (p. 432)

sensory adaptation the tendency for some sensory receptors to become less sensitive when stimulated repeatedly (p. 543)

set point the optimal value for a given variable of a system (p. 432)

sex ratio the relative proportion of males and females in a population (p. 597)

sigmoid curve (logistic) an S-shaped curve, typical of population growth that starts slow, accelerates or grows rapidly, and then levels out over time (p. 606)

silent mutation a mutation that does not alter the resulting sequence of amino acids (p. 340–341)

simple diffusion the ability of small and non-polar substances to move across a membrane unassisted (p. 90)

SINEs (short interspersed nuclear elements) repetitive DNA sequences, approximately 500 bp in length on average, interspersed throughout the genome (p. 347)

single nucleotide polymorphism (SNP) a difference in the DNA between individuals caused by point mutations (p. 340)

single-strand binding protein (SSB) a replication enzyme that prevents parent DNA strands from annealing to each other once they have been separated by helicase (p. 284)

small ribonucleoprotein (snRNP) a protein that binds to introns and signals them for removal (p. 322)

smooth ER areas of the endoplasmic reticulum without attached ribosomes (p. 75)

solenoid a group of six nucleosomes (p. 291)

somatic gene therapy a process in which therapeutic genes are transferred into somatic cells to treat a genetic disease (p. 391)

somatic system a subdivision of the efferent system (within the PNS); composed of efferent (motor) neurons that carry signals to skeletal muscles in response to external stimuli (p. 519)

specific heat the amount of thermal energy required to raise the temperature of a given quantity of a substance by 1 °C (p. 19)

spermatogenesis the production and development of sperm cells in the testes (p. 500)

spinal nerves the 31 pairs of nerves within the somatic system that transmit motor, sensory, and autonomic signals between the spinal cord and the rest of the body (p. 537)

spliceosome an enzyme-protein complex that removes introns from the mRNA (p. 322)

spontaneous change a change that will, once begun, continue on its own under a given set of conditions; does not require a continuous supply of energy (p. 135)

spontaneous mutation a mutation that is caused by an error in DNA replication (p. 342)

start codon (initiator codon) the codon that signals the start of a polypeptide chain and initiates translation (p. 317)

steroid a lipid that is composed of four carbon rings (p. 36)

steroid hormone a hormone composed of cholesterol that is not very water soluble; usually passes through the cell membrane and acts on receptors inside the cell (p. 469)

sterol a type of steroid with an OH group at one end and a non-polar hydrocarbon chain at the other (p. 84)

sticky end the end that remains after restriction enzymes cut on a zigzag across a DNA strand; a sticky end of a DNA fragment can form hydrogen bonds with a complementary sticky end on any other DNA molecule that has been cut by the same enzyme (p. 367)

stomata small pores in the surface of a leaf that can be opened and closed to control the exchange of gases between the atmosphere and the leaf interior (p. 231)

stop codon a codon that signals the end of a polypeptide chain and causes the ribosome to terminate translation (p. 317)

structural genomics the study of the structure of genes and their locations in a genome, as well as the analysis of the nucleotide sequences to locate genes within the genome (p. 382)

substantia gelatinosa (SG) a band of grey matter in the spinal cord that, when stimulated, produces a neurotransmitter that communicates with an injured region of the body; a simultaneous signal to the brain results in the perception of pain (p. 539)

substitution the replacement of one base pair in a DNA sequence by another base pair (p. 340)

substrate a substance that is recognized by and binds to an enzyme (p. 50)

substrate-level phosphorylation the formation of ATP by the direct transfer of a phosphate group from a substrate to ADP (p. 169)

supercoiling the continuous twisting of prokaryotic DNA that reduces the volume of the DNA (p. 293)

survivorship curve a graphic display of the rate of survival of individuals over the lifespan of a species (p. 595)

sustainable agriculture (low-input agriculture) the growth of food using less energy and fewer resources than industrialized agriculture uses (p. 660)

sympathetic division one of two subdivisions of the autonomic nervous system; increases energy consumption and prepares the body for action (p. 519)

synapse a functional connection between neurons or between neurons and effectors (p. 522)

synaptic cleft the tiny gap between presynaptic and postsynaptic cells in a chemical synapse, across which the neurotransmitter diffuses (p. 522)

synthetic hormone a hormone created by humans that behaves like a natural hormone (p. 491)

T

TATA box a region of the promoter that enables the binding of RNA polymerase (p. 319)

telomerase an enzyme that adds new telomere sequences to the ends of chromosomes (p. 296)

telomere a repeating sequence of DNA at the end of a chromosome that protects coding regions from being lost during replication (p. 293)

template strand the DNA strand that is copied into an mRNA molecule during gene transcription (p. 315)

termination sequence a sequence of bases at the end of a gene that signals the RNA polymerase to stop transcribing (p. 320)

testosterone the main male sex hormone, which stimulates and controls the development of male secondary sexual characteristics (p. 490)

thalamus the brain region that interprets sensory input and signals the cerebrum (p. 534)

thermal acclimatization the process by which an animal gradually adjusts to temperature changes in its environment (p. 438)

thermoregulation the regulation of internal temperature by negative feedback mechanisms (p. 436)

threshold potential the potential at which an action potential is generated by a neuron (p. 524)

thyroid gland an endocrine gland located in the throat that is regulated by the hypothalamus-pituitary system (p. 478)

topoisomerases a class of enzymes that relieve tensions caused by the unwinding of parent DNA; they cleave one or two of the DNA strand(s), allow the strands to untwist, and then rejoin the strand(s) (p. 284)

torpor a short-term state of reduced metabolic rate and body temperature that reduces the demand for energy during the night or day (p. 439)

traditional agriculture the growth of food by hand, using natural fertilizers and pesticides (p. 656)

transcription mechanism by which the information coded in nucleic acids of DNA is copied into the nucleic acids of RNA; something rewritten in the same language (p. 313)

transduction the use of viral vectors to introduce new genetic material into a cell (p. 352)

transfer RNA (tRNA) a carrier molecule that binds to a specific amino acid and adds the amino acid to the growing polypeptide chain (p. 315)

transformation a change in a genotype or phenotype caused by the direct uptake of genetic material by a cell (p. 274)

transgenic organism (genetically modified organism, GMO) an organism that has been modified to carry genes it does not normally carry (p. 386)

transition state a temporary condition during a chemical reaction in which the bonds in the reactants are breaking and the bonds in the products are forming (p. 129)

translation mechanism by which the information coded in the nucleic acids of RNA is copied into the amino acids of proteins (p. 313)

translocation the movement of entire genes or sequences of DNA from one chromosome to another (p. 342)

transport protein an integral membrane protein that provides a pathway for molecules to cross a membrane (p. 90)

transposon a small segment of DNA that can move to a different position in the genome (p. 347)

triglyceride a fat; three fatty acid chains linked to a glycerol molecule (p. 34)

trophic level one level of a food web (p. 658)

type 1 diabetes a type of diabetes caused by an inability to produce insulin (p. 366)

type 2 diabetes a type of diabetes caused by low insulin or an inability to use insulin (p. 366)

U

unsaturated fat a lipid that is composed of unsaturated fatty acids with double bonds in their hydrocarbon chain (p. 35)

V

vaccine an injection of a dead or inactivated virus to spur an immune response (p. 646)

vacuole a liquid-filled organelle that stores waste and aids in cellular metabolism and water balance (p. 75)

valence electron an electron in the outermost energy level or shell of an atom (p. 11)

van der Waals forces very weak attractions between two molecules, or parts of molecules, when they are close together (p. 15)

variable number tandem repeats (VNTRs) non-coding, repeating sequences of DNA that vary in length between homologous chromosomes and between individuals (p. 346)

vector a DNA molecule that is used as a vehicle to transfer foreign genetic material into a cell, for example, a plasmid (p. 368)

vesicle a small, membrane-bound organelle that may transport, store, or digest substances within a cell (p. 75)

W

wax a lipid that is formed when long fatty acid chains are joined to alcohols or carbon rings (p. 37)

white matter the tissue of the brain and spinal cord, composed primarily of axons of neurons; in the spinal cord, it surrounds the grey matter (p. 531)

whole-genome shotgun method a DNA sequencing method that involves blowing DNA strands into many fragments and then using computer technology to sequence and reassemble the fragments (p. 380)

Z

zero population growth (ZPG) a situation in which the death rate and the birth rate are in equilibrium (p. 602)

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